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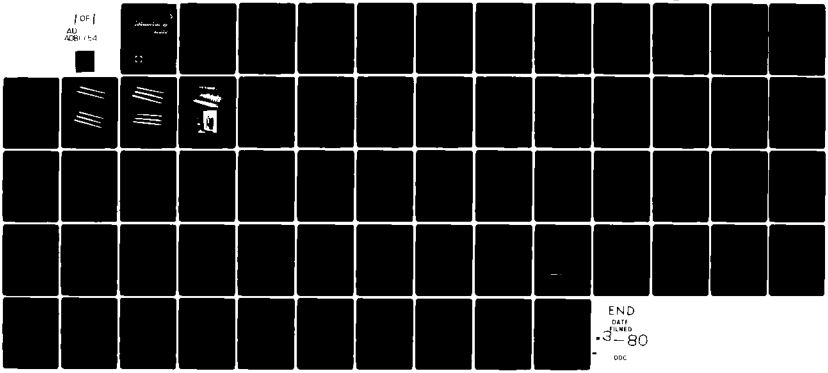

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author: T. Roe, Jr., J. F. Jenkins, and R. L. Alumbaugh, Ph D

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CIVIL ENGINEERING LABORATORY
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Port Hueneme, California 93043

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INTRODUCTION

The rapid corrosion of heat exchangers in air conditioning and refrigeration equipment, especially in tropical marine areas, is a major maintenance and energy use problem. In a brief survey conducted by the Civil Engineering Laboratory (CEL) (Ref 1), it was learned that at Subic Bay 90% to 95% of all air conditioning and refrigeration units have liquid-to-air heat exchangers; at Guam and Diego Garcia, nearly 100% of these units are used because of a water scarcity. Corrosion at Subic Bay is not severe because the prevailing wind is over land and because rainfall is high. Corrosion is severe at Guam and extremely severe at Diego Garcia. For example, uncoated copper tube/aluminum fin heat exchangers last less than 1 year at some Diego Garcia locations. In contrast, aluminum fin condenser coils located within 1 mile of the ocean at San Diego have a life expectancy of 5 years and a minimum life of from 2 to 3 years. Heat exchangers are periodically washed at Subic Bay, and this practice has started at San Diego, but is not done at Guam or at Diego Garcia. The reasons for not doing this at the latter two locations may be high labor costs or a general lack of maintenance procedures, as well as a scarcity of water.

Protective coatings, which are applied to metal surfaces exposed to aggressive environments, have not been widely used on heat exchangers because of a consequent initial decrease in heat transfer. However, Lee (Ref 2) reported that the application of a thin protective coating on gas-to-gas, liquid-to-gas, and liquid-to-liquid heat exchangers has only a small effect on heat transfer. Furthermore, in a 28-day field trial on steel pipe, liquid-to-liquid heat exchangers, Lee found that the heat transfer coefficients of the coated heat exchangers remained constant. The coefficients of the uncoated exchangers decreased to values below those of the coated units within the trial period. Oldberg (Ref 3) concluded from his study of compact military heat exchangers that the standard brazed aluminum construction must have an organic or equally resistive coating for protection against high salt atmospheres which exist in many areas of the world.

In a second phase of his work, Oldberg (Ref 4) reported that an all-aluminum exchanger (Type 3003 tube and Type 7072 fins) showed less corrosive attack than did the copper tube/aluminum fin units; and phenolic coatings of approximately 0.001 inch (1.0 mil, 0.0025 cm) thickness considerably improved the corrosion resistance of the all-aluminum unit, which looked good after 31 months of exposure in the Canal Zone.

At Patrick Air Force Base (Ref 5), where the air contains hydrogen sulfide and salt spray, the service life of uncoated all-copper heat exchangers is 6 to 7 years; when these units are coated with 3 mils of a

proprietary phenolic coating, the service life is over 8 years and the cost increase is one-third. Some doubt exists concerning the integrity of the bond when this material is applied to copper tube/aluminum fin units. Patrick AFB also tried sticky oil as a corrosion preventive, but this material collects dirt.

The Long Beach Naval Shipyard (Ref 6) reported that aluminum tube/aluminum fin condenser coils on window air conditioners in a marine environment lasted 3-4 years. Application of a chromium-chromate conversion coating by the Iridite process increased the life to 7 or 8 years. Copper tube/copper fin units performed very well but were much more expensive than the all aluminum units.

For its study, CEL also decided to investigate nonferrous, finned tube, liquid-to-gas heat exchangers of the type found on air conditioning or refrigeration equipment which use air condensers.

The approach was to record the temperature drop across each heat exchanger because this would indicate heat loss and, therefore, cooling efficiency. This drop would be recorded as a function of time over a long enough period to attain severe deterioration of uncoated exchangers. The long-term effects of the coatings selected could then be determined based on their thermal behavior, and compared with the results for both coated and uncoated exchangers. Information could also be obtained on relative service lives of the different types of heat exchangers.

EXPERIMENT DESIGN

Heat Exchangers

The twelve heat exchangers were purchased from The Vulcan Radiator Company, Hartford, Conn. All of the heat exchangers had the following characteristics:

1. Tube - 1 in. (2.54 cm) ID nominal and 1-1/8 in. (2.86 cm) OD with a wall thickness of 0.025 in. (0.064 cm) and a length of 6 ft (1.83 m)
2. Fins - hard-tempered plate type embedded in the tube, which is mechanically expanded to the diameter of the hole in the fins; nominal 3-1/4 in. (8.26 cm) square; 0.020 in. (0.051 cm) thick; and spaced 33/ft (108/m)

The materials or material combinations were:

1. Copper tube with copper fins.
2. Copper tube with aluminum fins coated with a synthetic enamel.*
3. Aluminum tube with aluminum fins.

*This coating was removed before the cleaning process described in the next section was done.

The copper used was essentially pure copper; the aluminum was 5005 alloy with an H-19 hardness.

Cleaning and Coating of Heat Exchangers

The heat exchangers were taken to the Guaranteed Products Division, DG Shelter Products, City of Industry, Calif., for cleaning and for coating of one set of the three types. The procedures were as follows:

1. Copper tube/copper fin and copper tube/aluminum fin:

   - Cleaner (detergent plus 6% Oakite), 3 min at 150°F (66°C)
   - Rinse, 2 min at room temperature
   - Deoxidizer (DESMUT) (Oakite LNC containing sulfuric acid), 10 sec at room temperature
   - Rinse, 2 min at room temperature
   - Cleaner, 3 min at 150°F (66°C)
   - Rinse, 2 min at room temperature
   - Place three copper tube/copper fin heat exchangers and three copper tube/aluminum fin heat exchangers in individual plastic bags for return to CEL
   - Paint one copper tube/copper fin heat exchanger and one copper tube/aluminum fin heat exchanger with Sherwin Williams H74BC23 POWERCLAD enamel (black) at 150V DC maximum, 2,000 amp
   - Bake painted heat exchangers; dry film thickness of coating, 0.6 mil (0.0015 cm)
   - Place coated heat exchangers in individual plastic bags for return to CEL

2. Aluminum tube/aluminum fin:

   - Cleaner (detergent plus 6% Oakite), 3 min at 150°F (66°C).
   - Rinse, 2 min at room temperature
   - Caustic etch (4% sodium hydroxide solution), 4 min at 120°F (49°C)
   - Rinse, 2 min at room temperature
   - Deoxidizer (DESMUT) (Oakite LNC containing sulfuric acid), 1-1/4 min at room temperature

- Rinse, 2 min at room temperature
- Rinse in deionized water at room temperature
- Place three aluminum tube/aluminum fin heat exchangers in individual plastic bags for return to CEL
- Paint one aluminum tube/aluminum fin heat exchanger with Sherwin Williams H74BC23 POWERCLAD enamel (black) at 150V DC maximum, 2000 amp
- Bake painted heat exchanger; dry film thickness of coating, 0.8 mil (0.0020 cm)
- Place coated exchanger in plastic bag for return to CEL

One set of three heat exchangers was coated, by dipping, at CEL as follows:

- One coat of MIL-P-15328C primer (wash) pretreatment (blue), Formula 117B, for metals
- One coat of TT-P-645 primer, zinc chromate, alkyd type (edges of fins were dipped twice)
- One coat of TT-E-489 enamel (black), alkyd, gloss

One set of three heat exchangers was coated, by dipping, at CEL; the procedures were as follows:

1. Copper tube/copper fin and copper tube/aluminum fin:

    - Brush sandblast
    - One coat Dimetcote No. 3 zinc inorganic silicate (edges of fins were dipped twice)

2. Aluminum tube/aluminum fin:

    - One coat of Dimetcote No. 3 (edges of fins were dipped twice)

A micrometer was used to measure fin and dry film thicknesses. Data on thickness of the coating systems applied at CEL are presented in Tables 1 and 2.

One set of three heat exchangers was left uncoated.

All sets of the exchangers were photographed before installation in the exposure facility (Figures 1 through 4).

Exposure Facility

A facility in which to expose the heat exchangers was designed at CEL. Required components were either purchased or were fabricated by CEL. The facility (Figure 5) consists of:

1. A bench assembly
2. An inlet header
3. 12 thermocouples to measure the temperature of the inlet fluid going to each of the 12 heat exchangers
4. An outlet header
5. 12 thermocouples to measure the fluid outlet temperature for the 12 heat exchangers
6. 12 flow meters each with a valve for flow adjustment
7. A 52-gallon electric water heater
8. A circulating pump (Figure 6)
9. All necessary piping and valves

All exposed piping was jacketed with fiberglass insulation covered with aluminum sheeting. Thermocouple (copper-constantan) outputs were fed to two recorders located inside the adjacent building. When one of these recorders failed during the first month of operation, both recorders were replaced by a 24-channel strip chart recorder.

The 12 heat exchangers were installed in random order on the test facility; the test fluid (approximately 1:1 solution of engine anti-freeze and tap water) was added to the system; and a checkout was started. After it was determined that the system did not leak, the water heater was set for 140°F (60°C)* and turned on. Each flow meter control valve was adjusted so that the flow meter scale reading was 50%,** or 0.39 gpm (1.48 l/m), of liquid with a specific gravity of 1.054 at 130°F (54°C). Operation of the equipment was checked at the beginning and close of each working day.

Heat loss across each exchanger was determined by recording the inlet and outlet temperatures. The 24-channel strip chart recorder produced a data point approximately every 3 minutes. Temperature differences were read from the chart paper and entered on specially prepared data forms, each of which had spaces for two sets of 13 or 14 temperature-drop readings per heat exchanger. When the voluminous data obtained was reviewed by a CEL mathematical statistician, he suggested that at approximately 1-month intervals 13 or 14 temperature-drop readings be averaged for each heat exchanger. Thus, the exchangers could be ranked in decreasing order of cooling efficiency.

On completion of the operation, a review of the data indicated that much more meaningful conclusions could be obtained by calculation of the heat transfer rate for each heat exchanger approximately weekly, and at, or near, a time when the ambient temperature was known. The time chosen

*Compression temperature for Freon-12 is approximately 110°F (43.4°C) and for Freon-11 is 120°F (48.9°C).

**Fluid velocity in 1-inch (2.54-cm) ID tubing was 0.16 ft/sec.

was 1600 hours (4:00 p.m.), although this time could vary by ±30 minutes. The heat transfer rate H, in Btu/hr-°F/ft length* of the heat exchanger, was determined by the following equation:

$$H = \frac{m\,C_p}{L} \log_e \left(\frac{T_i - T_a}{T_o - T_a} \right)$$

where m = fluid through the exchanger, lb/hr

C_p = specific heat of the liquid, Btu/lb-°F

L = length of the heat exchanger, ft

T_i = inlet fluid temperature, °F

T_o = outlet fluid temperature, °F

T_a = ambient temperature, °F

The ratios of the heat transfer rates of coated versus uncoated exchangers for each coating type and exchanger material type were calculated on a monthly basis for two years, and linear regression curves were computer-plotted so that performance comparisons of uncoated and uncoated versus coated exchangers could be made. This report includes data selected at approximately 1-week intervals between 29 Jun 1976 and 11 Aug 1978. A time extension beyond the planned 29 Jun 1978 completion of a 2-year operation was necessary because the equipment was shut down from 8 Jul to 19 Sep 1977 when the test area was paved.

Heat transfer ratios are shown in Figures 7 and 8, and data points and regression curves for coated versus uncoated copper tube/copper fin heat exchangers are shown in Figures 9, 10, and 11.

Concurrent with the operation described above, the exchangers were examined for evidence of corrosion. After the Apr 1978 inspection (Table 3), it was decided to attempt accelerating the rate of corrosion. A small cordless electric yard and garden sprayer was used to spray approximately 1 quart (0.95 liter) of seawater on the heat exchangers every morning of each working day, weather permitting. After the completion of 2 years of operation the exchangers were inspected and the results are shown in Table 4.

FINDINGS

The test data obtained during this investigation are shown in graphical form in Figures 7 through 11. Figures 7a and 7c show the negative effect of coatings on the heat transfer performance of aluminum tube/aluminum fin and copper tube/aluminum fin exchangers. Figure 7b shows that all three coatings improved the heat transfer performance of copper tube/copper fin exchangers over that of an uncoated unit during

*Btu/sq ft not applicable to finned tubing.

the exposure period. For example, copper tube/copper fin exchangers coated with an electrostatic polyester coating were transferring 56% more heat than the uncoated all copper unit after 2 years; specification alkyd and zinc inorganic silicate coatings showed improvements of 45% and 63%, respectively, over uncoated surfaces. Each of these curves with its data points is shown in Figures 9 through 11.

Data plotted in Figure 8 allow comparisons of the performances of the various primary surfaces, both uncoated and coated. For uncoated exchangers, Figure 8a shows that after 24 months aluminum tube/aluminum fin exchangers are performing 57% better than copper tube/copper fin exchangers and 32% better than copper tube/aluminum fin units. When the units are coated with an electrostatic polyester coating (Figure 8b), the copper tube/copper fin units are superior to all the others. Much smaller differences occurred when the exchangers were coated with the specification alkyd or the zinc inorganic silicate materials (Figures 8c and 8d).

In summary, after a 2-year operation in a temperate marine environment at Port Hueneme, Calif., copper tube/copper fin heat exchangers coated with the three different systems were found to have a higher heat transfer capacity than the same unit in the uncoated condition. The zinc inorganic silicate and the specification alkyd coatings were found to be in better condition than was the electrostatically applied polyester coating. Conversely, the application of these coatings to aluminum tube/aluminum fin and copper tube/aluminum fin heat exchangers resulted in a lower heat exchange capacity than that of the uncoated units. Again, the zinc inorganic silicate and specification alkyd coatings were in better condition than the electrostatically applied polyester coatings.

DISCUSSION

Although the findings give an indication of the effect of coatings on the corrosion resistance and the heat transfer capacity of the three types of heat exchangers, variables such as bonding of the coating and coating thickness should be considered. For example, Guaranteed Products Division cleans and coats only aluminum extrusions for the building industry. They ran the heat exchangers with copper components in their cleaning baths in a minimum time because of a fear of possible copper contamination to the baths. As a result, the surface preparation of the copper was apparently not sufficient to assure proper bonding of the coatings. Also, the coatings applied at Guaranteed Products and at CEL were not modified for use on the heat exchangers. Thus, the effect of a thicker electrostatically applied polyester coating and thinner specification alkyd and zinc inorganic silicate coatings is not known, and needs to be investigated. In addition, an in-service evaluation of coated heat exchangers in a very aggressive environment should be carried out to determine their cost effectiveness in a relatively short time.

Any in-service evaluation should take into account the fact that a heat exchanger is probably overdesigned in order to compensate for loss of thermal efficiency as a result of corrosion. Thus, an exchanger

which is coated with a thermally efficient, corrosion-resistant material could be smaller in size. This would reduce costs and save additional energy by reducing pumping power requirements. In addition, the longer life expectancy would reduce maintenance costs, perhaps by one-half.

The only realistic costs for coated versus uncoated heat exchangers used in this study were for the all copper units. Current (1978) prices range from $43.00 to $53.80 each, depending on the quantity purchased. Costs of cleaning and coating are $0.01 per perimeter inch, or $25.75. Thus, coating increases the price by 48% to 60%. This should be justified on the basis of increased life expectancy alone. As stated previously, additional savings would accrue from lower initial costs (smaller units) and higher thermal and electrical (pumping) efficiencies. An excerpt from a cost-effectiveness study conducted at CEL is presented in the Appendix.

CONCLUSIONS

Based on a 2-year operation in a temperate marine environment, it is concluded that for application in this environment:

1. Copper tube/copper fin heat exchangers coated with an electrostatic polyester material (0.6 mil), a specification alkyd system (10.4 mils total), or a zinc inorganic silicate material (2.0 mils) are more thermally efficient (56%, 45%, and 63%, respectively) than an uncoated exchanger of this type after a 2-year operation in a temperate marine environment.

2. The three coating systems used had mostly a negative effect on thermal efficiency when applied to aluminum tube/aluminum fin and copper tube/aluminum fin exchangers.

3. Uncoated aluminum tube/aluminum fin heat exchangers are more thermally efficient than either the uncoated copper tube/copper fin or copper tube/ aluminum fin heat exchangers after a 2-year operation in a temperate marine environment.

ACKNOWLEDGMENTS

The authors wish to thank Mr. Joseph B. Crilly for his early work in this area, Mr. James Thayer for designing the test unit, Mr. Theodore Tree for assembling the test unit, Messrs. Albert F. Curry and Theodore Tree for assisting in the heat exchanger coating applications at CEL, Mr. Joseph C. Quigley for installation of the temperature recording equipment, Mr. Charles W. Mathews for assistance in data reduction, and Mr. Eddy S. Matsui for computer graphics.

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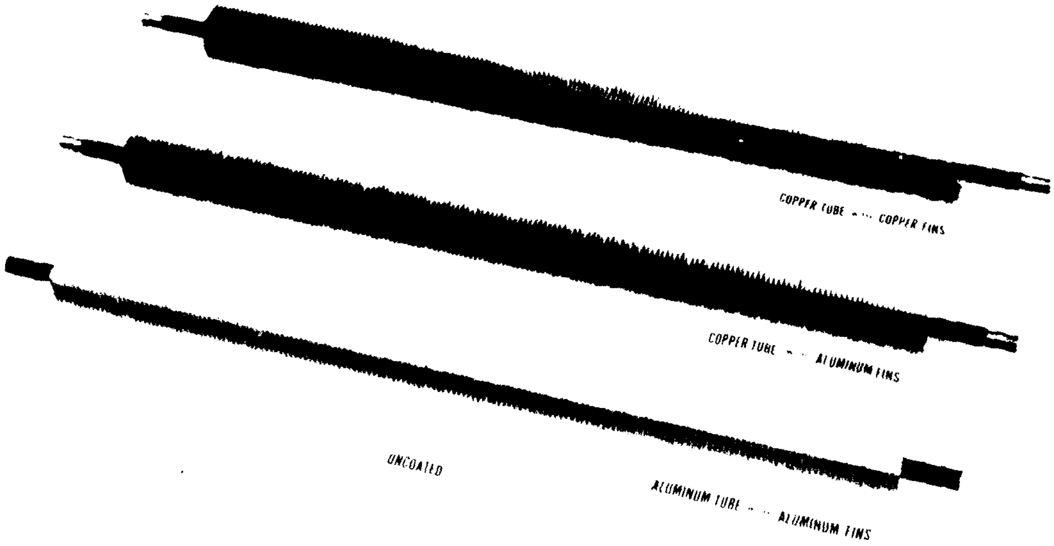


Figure 1. Uncoated heat exchangers.

Figure 2. Heat exchangers coated with an electrostatically applied polyester.

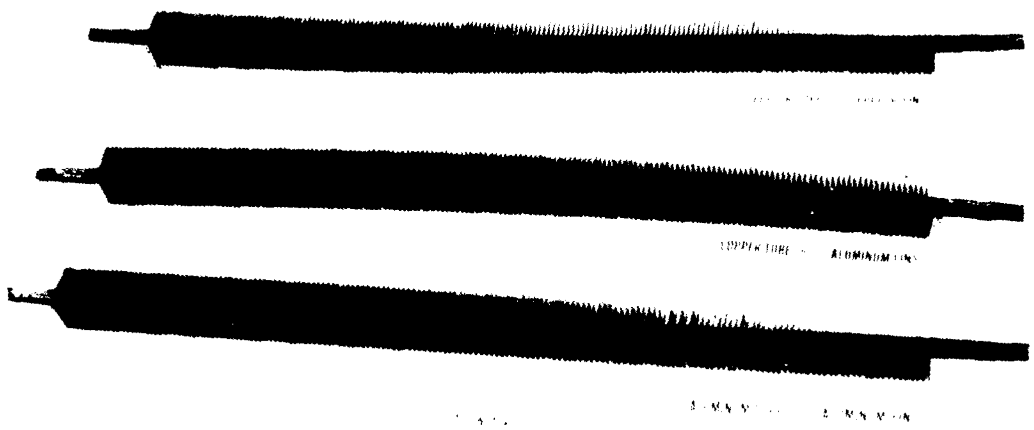


Figure 3. Heat exchangers coated with a specification alkyd system.

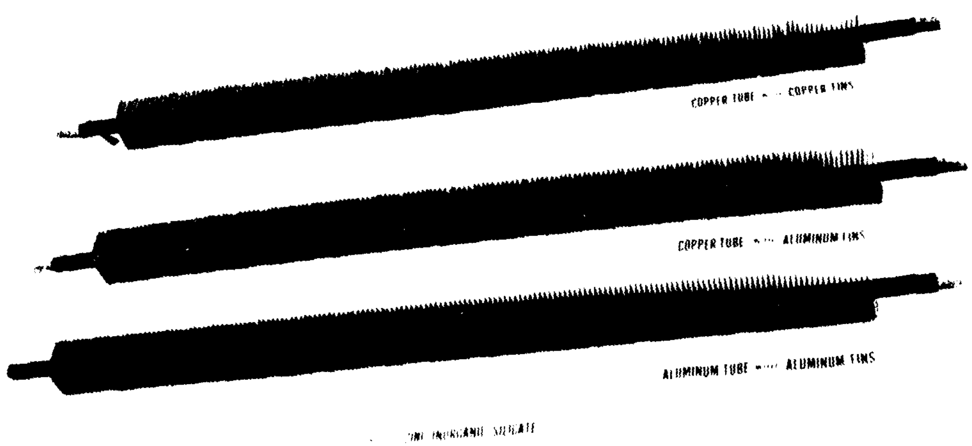


Figure 4. Heat exchangers coated with a zinc inorganic silicate, Dimetcote no. 3.

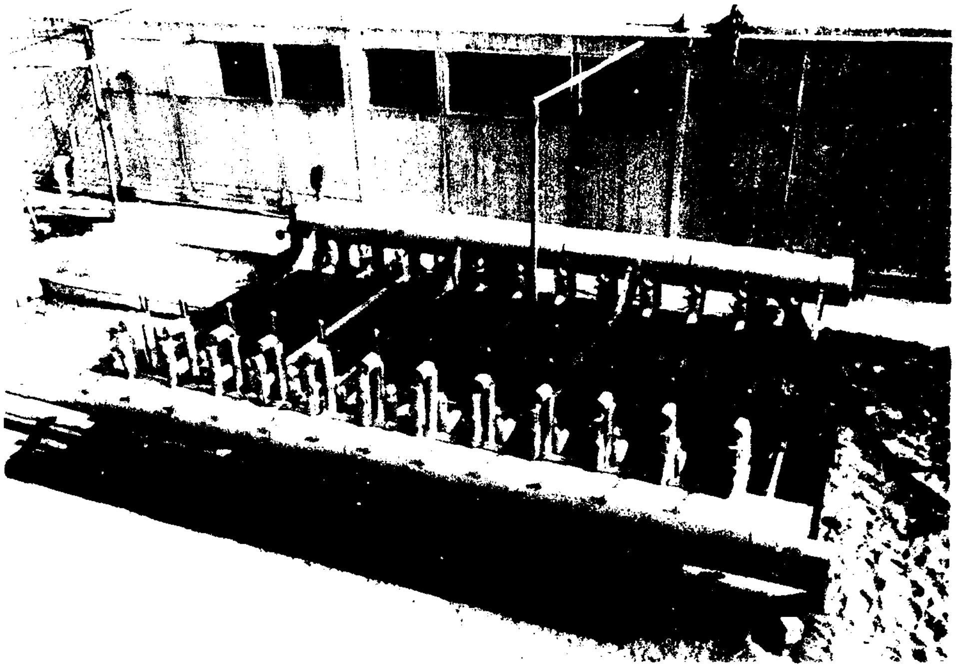


Figure 5. Heat exchanger test facility at CEL.

Figure 6. Water heater and circulating pump.

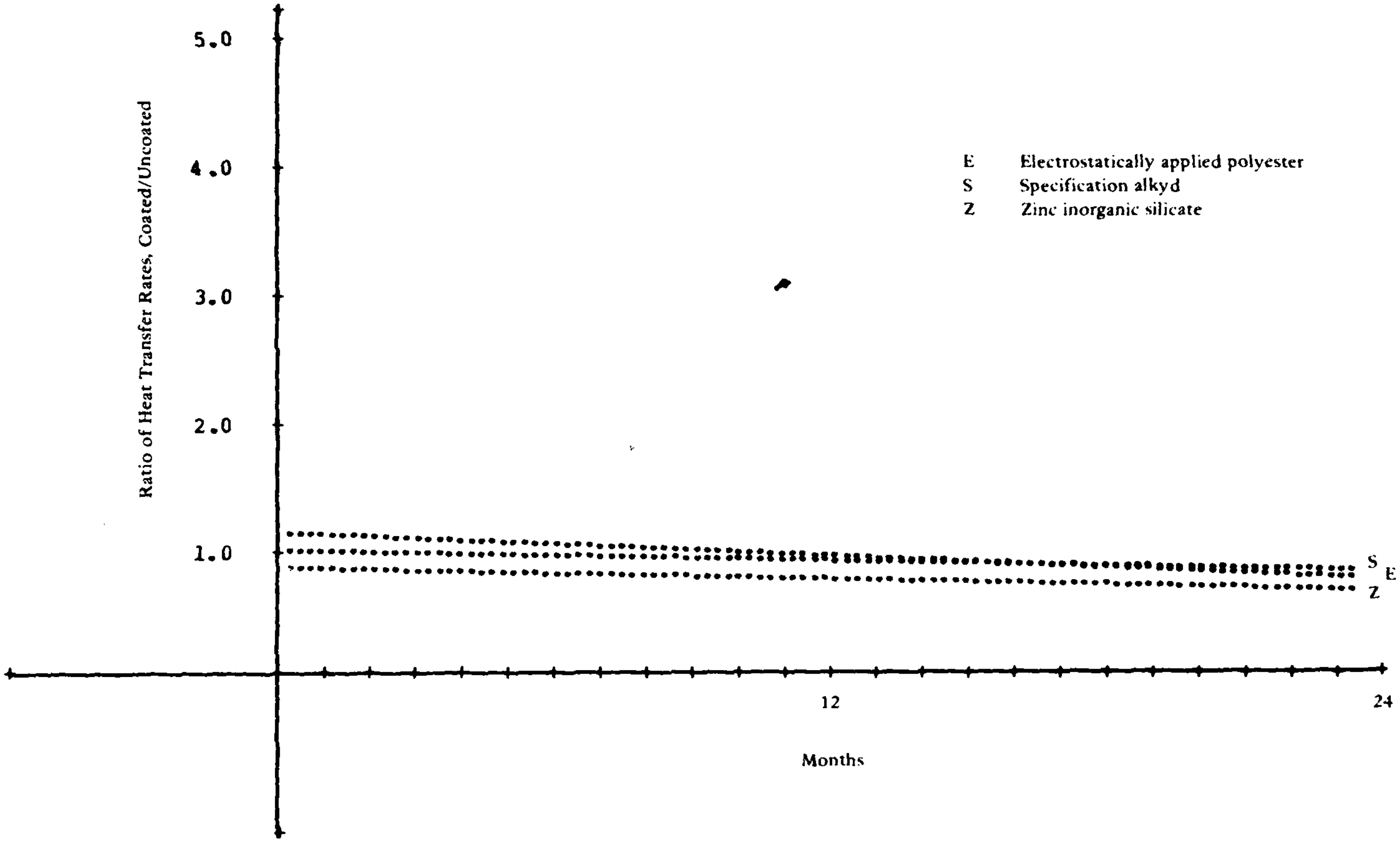
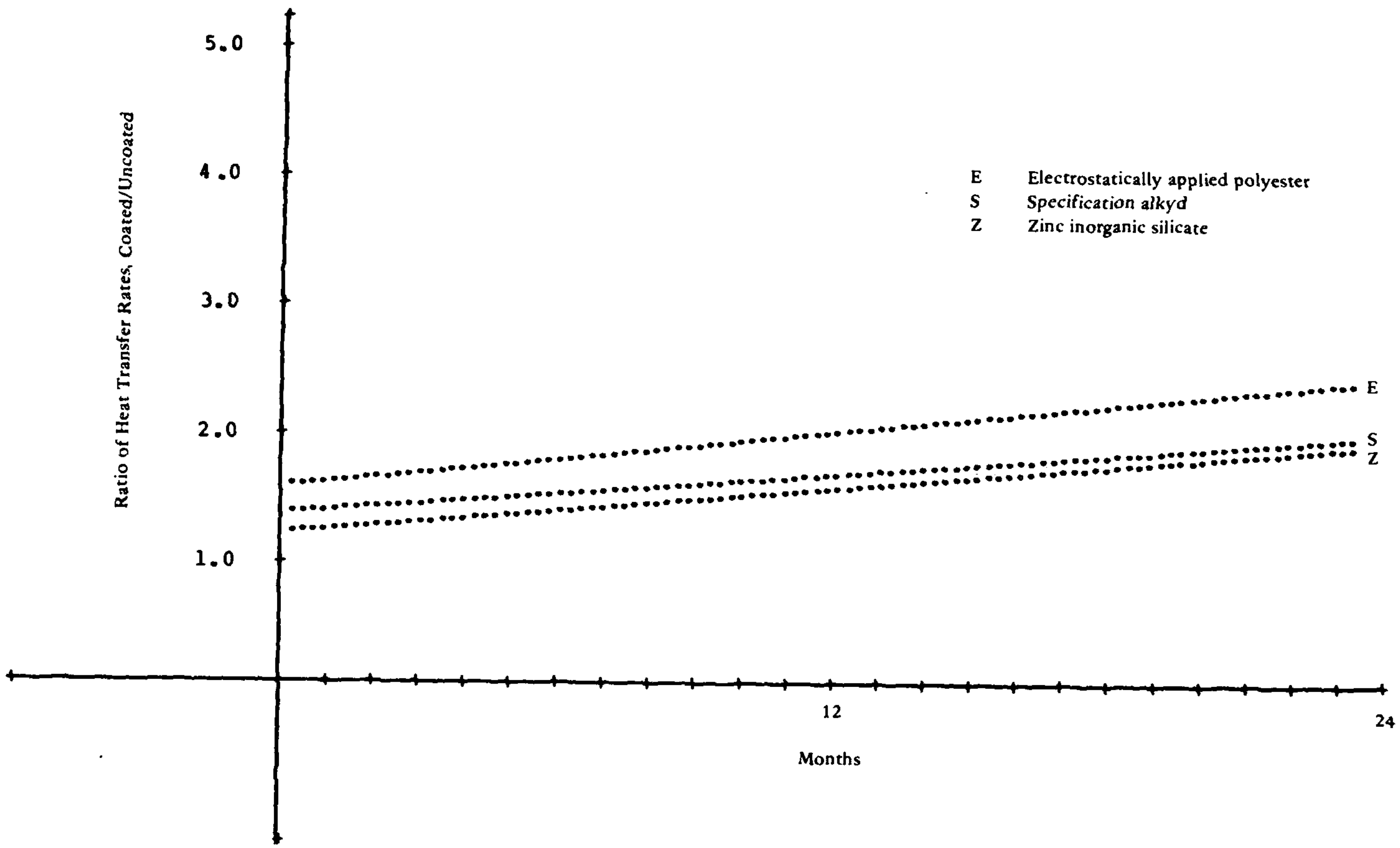
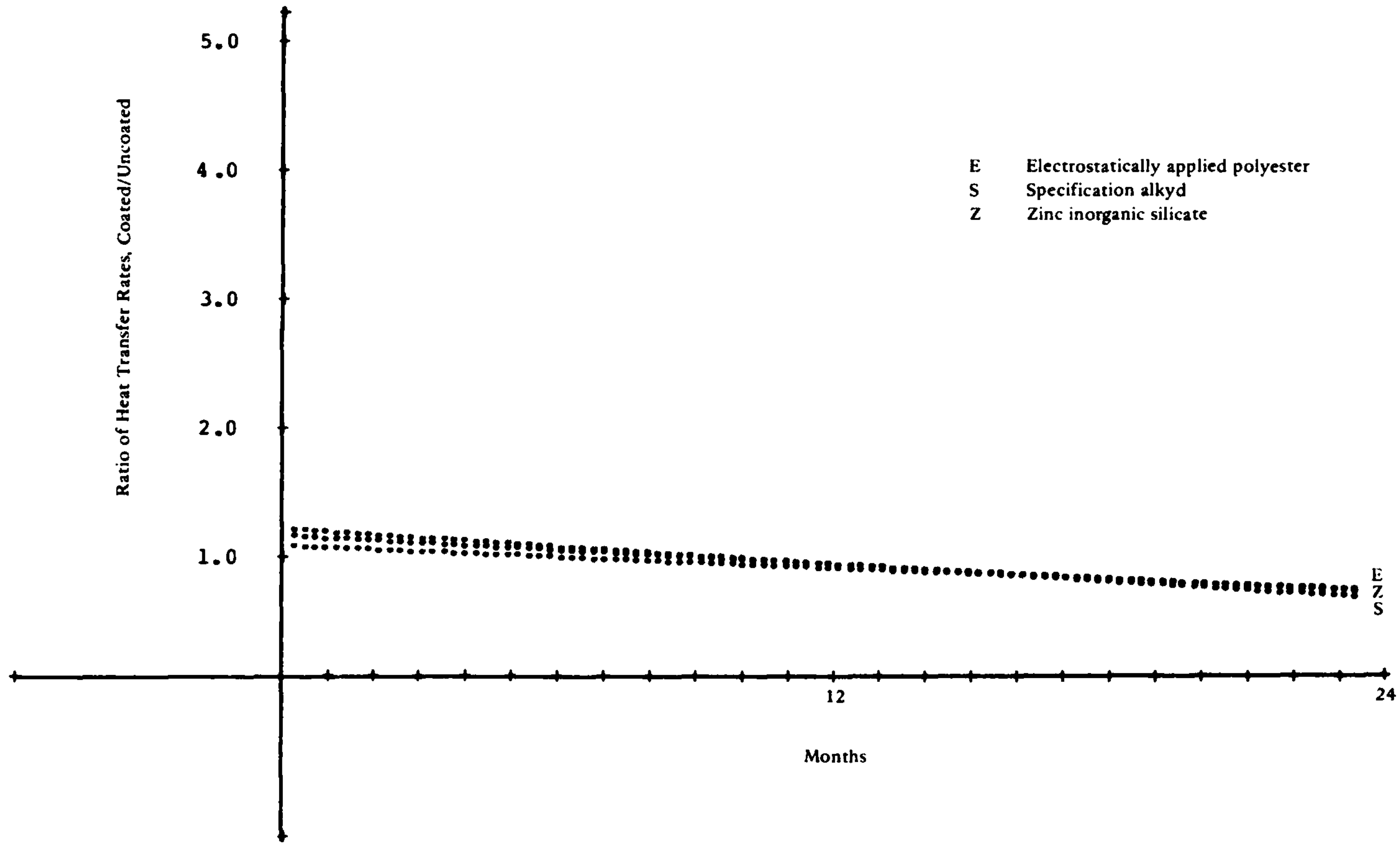


Figure 7. Ratios of heat transfer rates, coated versus uncoated heat exchangers.
(a) Aluminum tube/aluminum fin.



(b) Copper tube/copper fin.



(c) Copper tube/aluminum fin.

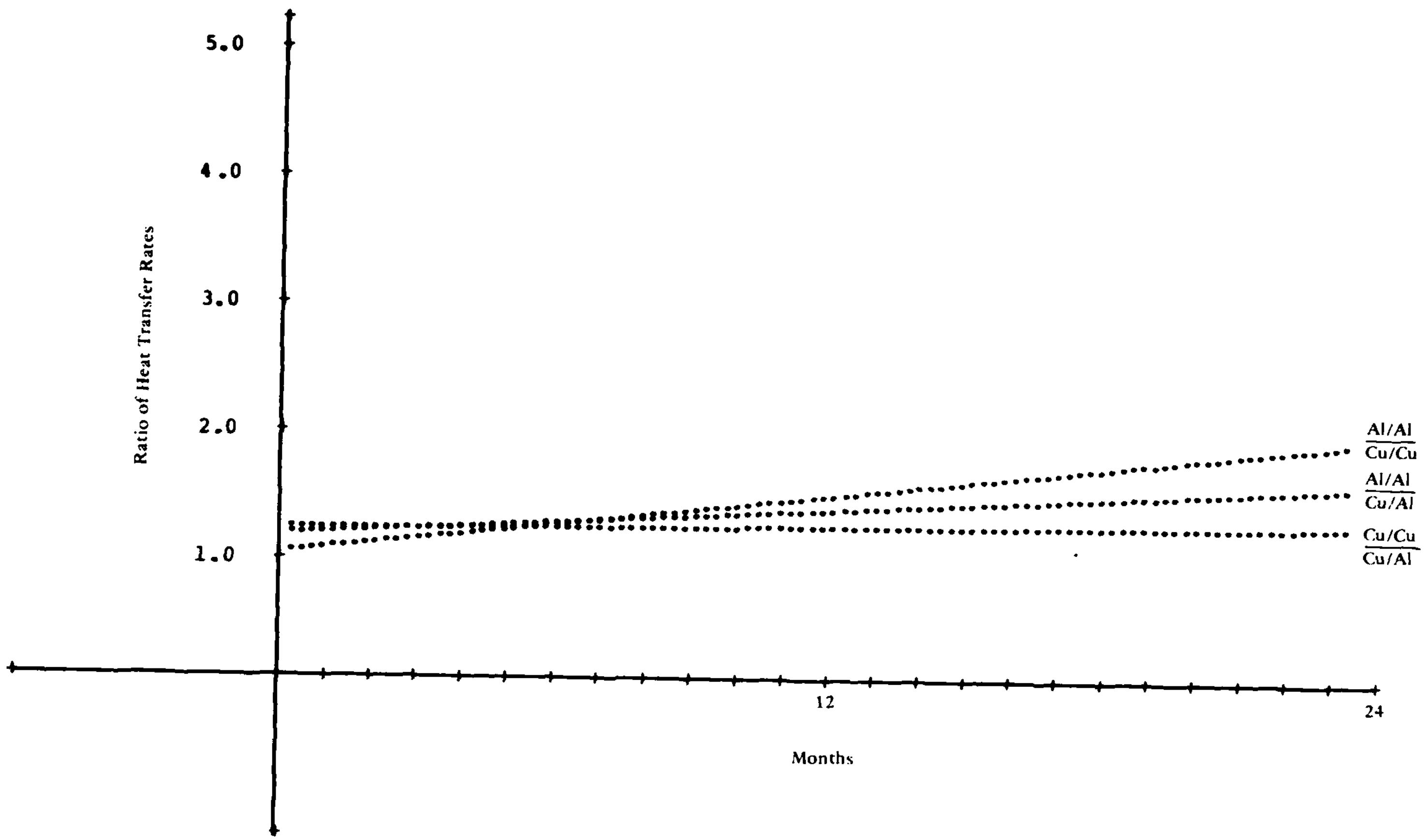
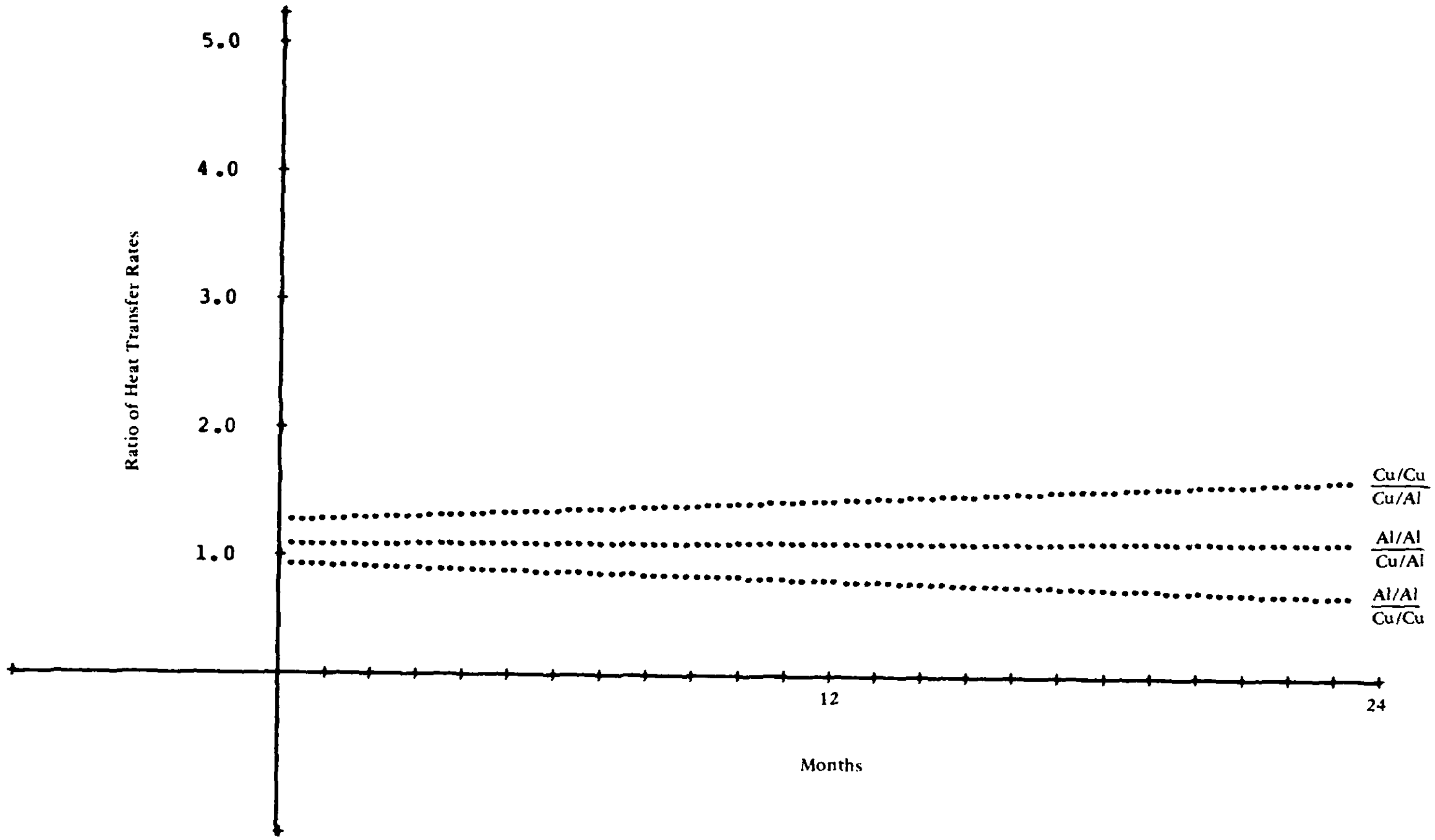
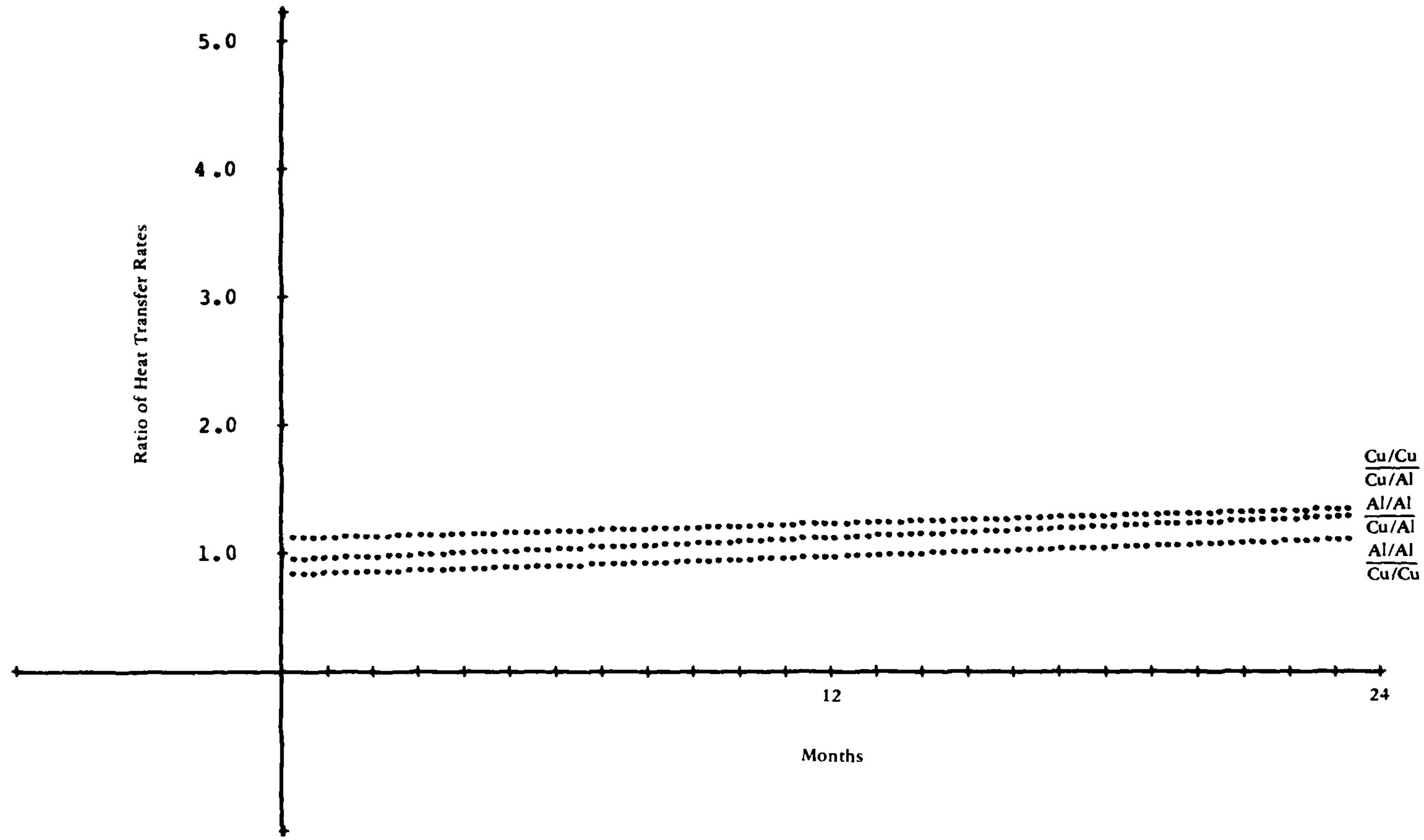


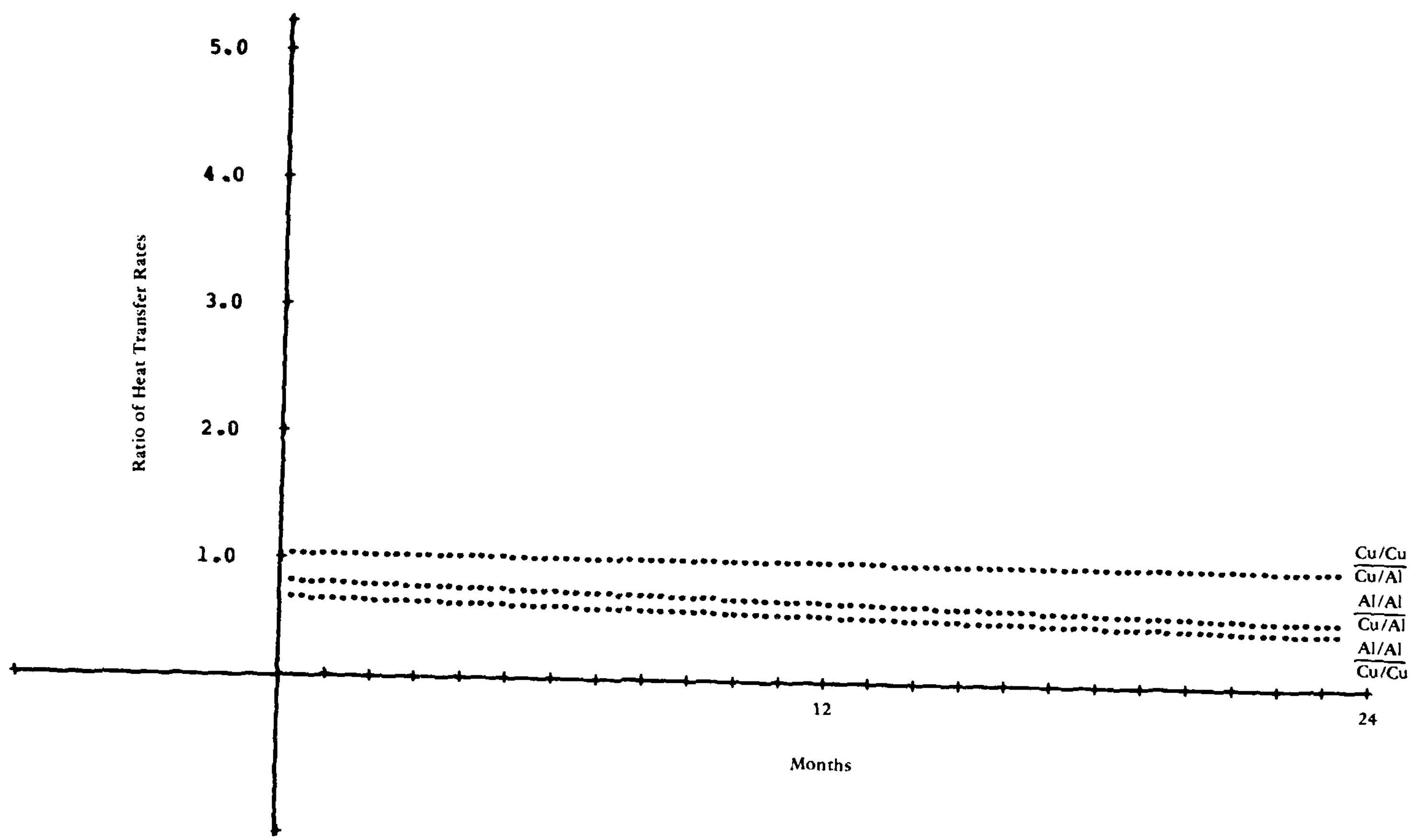
Figure 8. Ratios of heat transfer rates.
(a) Uncoated heat exchangers.



(b) Electrostatic polyester coated heat exchangers.



(c) Specification alkyd coated heat exchangers.



(d) Zinc inorganic silicate coated heat exchangers.

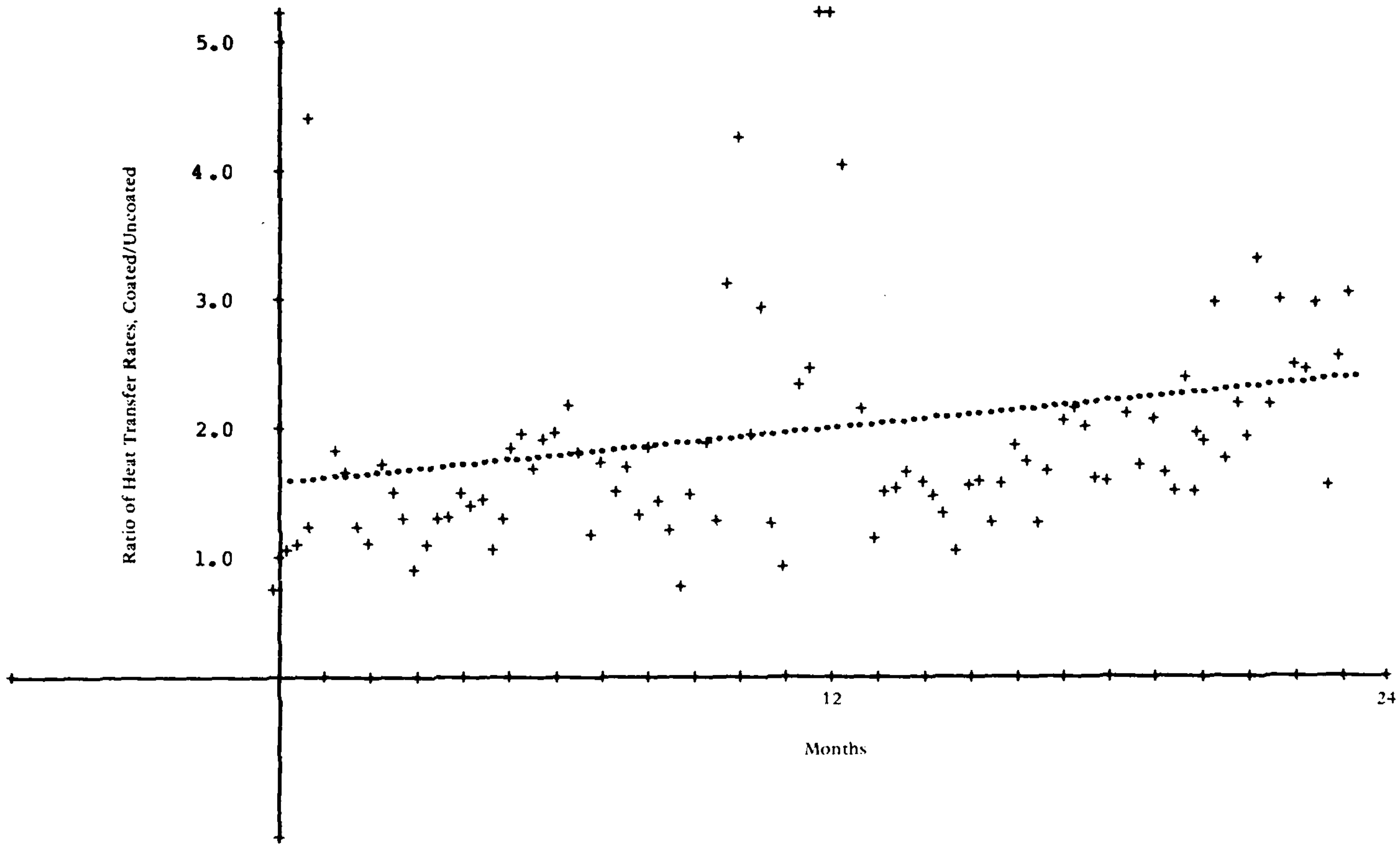


Figure 9. Ratio of heat transfer rates, electrostatically applied polyester coated versus uncoated copper tube/copper fin heat exchangers.

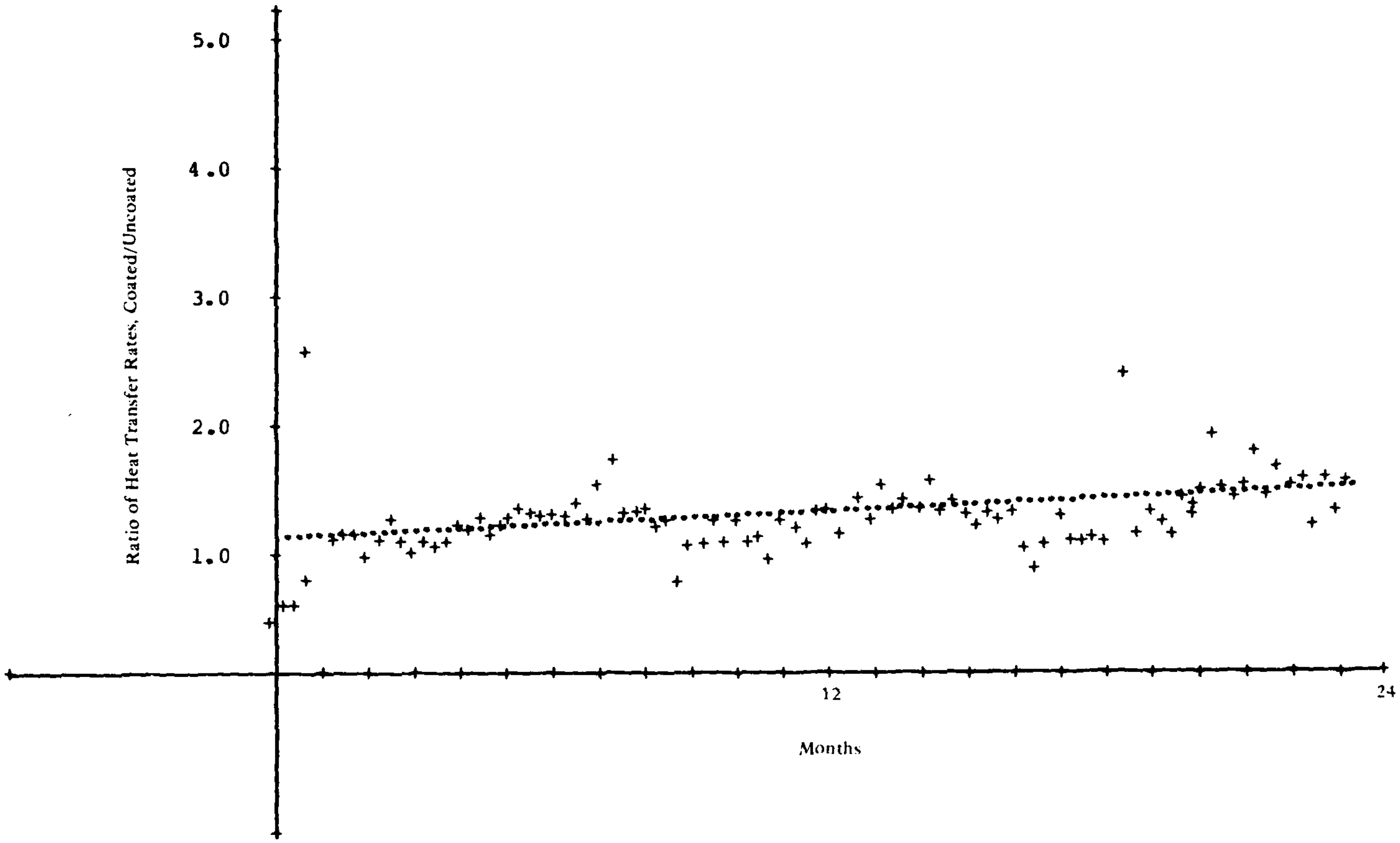


Figure 10. Ratio of heat transfer rates, specification alkyd coated versus uncoated copper tube/copper fin heat exchangers.

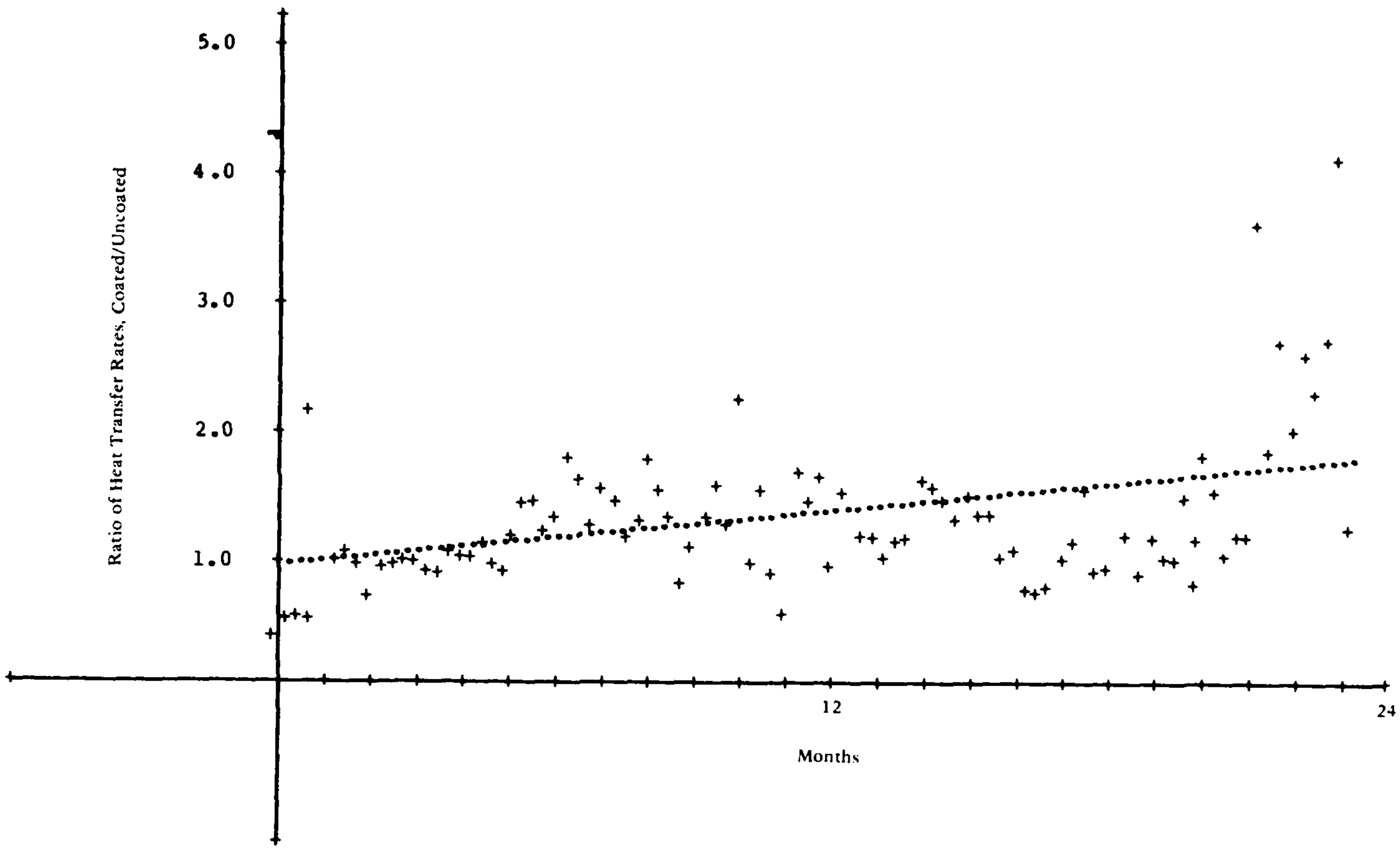


Figure 11. Ratio of heat transfer rates, zinc inorganic silicate coated versus uncoated copper tube/copper fin heat exchangers.

Table 1. Thicknesses of Specification Alkyd[a] Coating Systems Applied to Heat Exchangers

Heat Exchanger Material	Fin Thickness, mils (mm)	Dry Film Thickness, mils (mm)					Total	
		Formula 117B MIL-P-15328C Wash Primer	Formula 84 TT-P-645 Zinc Chromate Primer		TT-E-489 Alkyd Enamel, Black			
			Center	Edge	Center	Edge	Center	Edge
Aluminum tube/ Aluminum fin	17.3 (0.44)	1.0 (0.025)	2.5 (0.06)	4.1 (0.11)	2.6 (0.07)	4.3 (0.11)	6.1 (0.16)	9.4 (0.24)
Copper tube/ Copper fin	21.7 (0.55)	1.2 (0.031)	2.3 (0.06)	4.8 (0.12)	1.9 (0.05)	4.4 (0.11)	5.4 (0.14)	10.4 (0.26)
Copper tube/ Aluminum fin[b]	21.3 (0.54)	1.5 (0.038)	1.5 (0.04)	4.0 (0.10)	2.4 (0.06)	4.9 (0.12)	5.4 (0.14)	10.4 (0.26)

[a]Paint System MIL-P-15328C, TT-P-645, TT-E-489.

[b]The factory-applied synthetic enamel had been removed.

Table 2. Thickness of Zinc Inorganic Silicate[a] Coating Applied to Heat Exchangers

Heat Exchanger Material	Fin Thickness, mils (mm)	Dry Film Thickness, mils (mm)
Aluminum tube/ Aluminum fin	17.3 (0.44)	3.6 (0.09)
Copper tube/ Copper fin	23.1 (0.59)	2.0 (0.05)
Copper tube/ Aluminum fin[b]	19.3 (0.49)	4.4 (0.11)

[a]Dimetcote No. 3.

[b]The factory-applied synthetic enamel had been removed.

Table 3. Condition of Coated and Uncoated Heat Exchangers After 20 Months of Operation at Port Hueneme, Calif.

Heat Exchanger Material	Coating	Condition
Aluminum tube/ Aluminum fin	None	Very good; slight overall corrosion
	Electrostatic polyester	Very good; slight loss of coating on edges of fins
	Specification alkyd	Very good; some loss of top coat on edges of fins
	Zinc inorganic silicate	Very good; slight overall corrosion
Copper tube/ Copper fin	None	Good; overall corrosion, but heavier at the edges of the fins
	Electrostatic polyester	Very good; slight corrosion at the tube/fin joint and on edges of fins
	Specification alkyd	Very good; some loss of top coat on edges of fins
	Zinc inorganic silicate	Very good
Copper tube/ Aluminum fin	None	Very good; slight corrosion at tube/fin joint and on fins
	Electrostatic polyester	Slight corrosion at tube/fin joint; about 90% of the tube coating has flaked off
	Specification alkyd	Very good; some loss of top coat on edges of fins
	Zinc inorganic silicate	Very good; slight corrosion at tube/fin joint

Table 4. Condition of Coated and Uncoated Heat Exchangers After 24 Months of Operation[a]

Heat Exchanger Material	Coating	Condition
Aluminum tube/ Aluminum fin	None	Essentially unattacked, except at tube/fin interface where a thin continuous layer of white corrosion products extended approximately 1/16 in. along the tube surface. Fins were covered with uniformly distributed patches of white corrosion products, approximately 1/8 in. in diam and 10 patches/sq in. Lower half of each fin had a heavier deposit of corrosion products.
	Electrostatic polyester	Aluminum showing at tube/fin joint; slight corrosion on edges of fins
	Specification alkyd	Very good; some loss of top coat on edges of fins
	Zinc inorganic silicate	Very good; slightly mottled appearance
Copper tube/ Copper fin	None	Tube surfaces uniformly covered with a patina of malachite green corrosion products over a thin black (copper oxide) film; fin surfaces uniformly covered with a similar patina which was heavier on the lower half; no concentration of corrosion products adjacent to the tube/fin interface
	Electrostatic polyester	Corrosion on tube surface which appears bumpy; slight corrosion in spots on edges of fins
	Specification alkyd	Very good; some loss of top coat on edges of fins
	Zinc inorganic silicate	Very good; slightly mottled appearance

continued

Table 4. *Continued*

Heat Exchanger Material	Coating	Condition
Copper tube/ Aluminum fin	None	Tube surfaces covered with a thin dark (black) patina in some areas; adjacent to fins the original copper-colored surface was unaffected; at tube/fin interface was a moderately heavy accumulation of white corrosion products; fins were covered with uniformly distributed patches of white corrosion products approximately 1/8 in. in diam and 10 patches/sq in.; lower half of each fin had a heavier deposit of corrosion products
	Electrostatic polyester	Slight corrosion at tube/fin joint; about 90% of the tube coating has flaked off
	Specification alkyd	Very good; some loss of top coat on edges of fins
	Zinc inorganic silicate	Very good; slightly mottled appearance

[a]Exchangers sprayed with seawater once each working day, weather permitting, during the last 4 months of operation.

Appendix

COST EFFECTIVENESS

By Richard A. Boettcher

A short investigation was undertaken at CEL to develop a parametric, life-cycle cost analysis to include the necessary decision factors. The objective was: first, to make possible a decision on whether or not there is promise in coatings for air-cooled condensers of Navy air conditioning equipment; and second, if cost-effective, to develop a plan of action for CEL production of recommendations to NAVFAC on specifications or design criteria, as appropriate. The investigation included: (1) inquiries regarding equipment or maintenance; (2) inquiries of 11 equipment manufacturers and 5 coil fabricators, coil coaters, and suppliers of metal finishing products; (3) review of previous research on coil materials, coatings, and finishes; (4) an estimate of existing tonnage in Navy mechanical cooling installations; (5) determination of dominant cost elements and appropriate cost estimating methodology; and (6) preparation of a comparative life-cycle cost example.

A life-cycle cost example follows* and was developed to compare the cost effectiveness and energy-to-cost ratios for three condenser coils representing successively higher levels of performance over the current industry standard. The results of this analysis show that coil performance enhancement can be justified economically at all Navy locations where mechanical cooling is required or permitted.** A continuing research effort to produce definitive design criteria and purchase specifications for such higher performance, air-cooled refrigeration, and air conditioning condensers is clearly indicated and is recommended.

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*Copy of "Pay-Out and Energy/Cost Ratios; Comparative Example of Coated Heat Exchanger Applications," by Richard A. Boettcher.

**Locations like Charleston, S.C., are possible exceptions because of the shorter and less severe cooling season, moderately corrosive atmospheric conditions, low power costs, and relatively low cost of construction and maintenance; all of which combine to produce the operating conditions for which present commercial designs of packaged equipment appear to be optimized.

This investigation also included an estimate of installed Navy air conditioning and refrigeration/equipment cooling tonnage that employs air-cooled condensers.* Results are reported herein. In summary, an average annual saving of $15.7 million can be made; the average pay-out is 3.8 years for all environments; and an estimated annual electrical energy saving equivalent to 3.2 x 10^6 million Btu's could result, reducing the Navy's fuel oil dependency by almost 1,500 barrels per day.

Several conclusions are made as a result of this investigation:

1. CEL should develop an interdisciplinary program to continue research on air-cooled condenser design criteria.

2. Because cost-effective condenser designs for severe atmospheric exposures and areas of high energy costs are not necessarily cost-effective under other conditions, an air conditioning "tropicalization" specification may be appropriate.

3. Higher performance condensers should be considered for existing cooling units when condensers are replaced. For new units, any special Navy-specified condenser should be supplied with the equipment; field retrofit is not practical.

4. Condenser specifications that are cost-effective cannot be developed without consideration of industry standards and fabrication practices.

5. If materials, fabrication method, and coating specified are commercially available, industry can quote costs on high performance, Navy-specification condensers.

6. Frequency of coil washing has a significant effect (as high as 25%) on the power cost factor, and the estimates made herein are based on regular washing.

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*Copy of "The Status of Research and Development for Improving the Long-Term Performance of Air-Cooled Condensers in Marine Environments," by Richard A. Boettcher.

Pay-Out and Energy/Cost Ratios
Comparative Example of Coated Heat Exchanger Applications

Pay-outs and energy/cost (E/C) ratios are presented in tables 1-4 for four postulated coil types at four locations considered typical of the range of atmospheric corrosivity experienced at Navy shore activities, worldwide. Calculations were made for the following locations:

a. Severe environment - Table 1--Guam, Marshall Islands

b. Moderate environment - Table 2--Pearl Harbor, HI
Table 3--Charleston, SC

c. Mild environment - Table 4--El Centro, CA

These locations not only represent a range of atmospheric corrosivity[1] but also ranges of cooling requirements, power costs, and costs of construction/maintenance work.

Coil Types

The four coil types considered were termed the "standard" coil, an "improved" coil, a "superior" coil, and a "lifetime" coil. Where greater resistance to atmospheric corrosion can be justified than that of the standard commercial coil normally supplied as part of packaged equipment units, the improved, superior and lifetime coils are intended to provide successively higher levels of overall, life-cycle performance. Higher performance can be achieved by a combination of more corrosion resistant and mutually compatible materials for fins and tubing, the use of protective coatings or finishes, and increased coil heat transfer area.[2] Because of the high cost of coil replacement it is desirable that a coil have the same economic lifetime[3] as other components of the cooling unit.

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[1] Research by the U. S. Army Natick Laboratories on quantitative measurement of saltfall as a factor in atmospheric corrosivity is discussed in a Code L03B file memo dated 9 Apr 1979 entitled, "Estimating Coil Life and Relative Heat Transfer Based on Exposure"

[2] Industry, generally, has optimized condenser coil design variables that are more closely related to manufacturing operations and initial cost, such as fin thickness and mechanical properties, fin spacing and configuration for maximum heat transfer, and mechanical bonding methods that assure good conductivity between fins and tube. No changes to improve performance would be contemplated for these details.

[3] Per NAVFAC P-442, economic lifetime is the least of the mission life, the physical life, or the technological life and is the period of time during which positive benefit is provided to the Navy.

Considering only the effects of atmospheric corrosion, the expected service or physical life of standard condenser coils is much shorter in severe environments than the service life of other packaged components, as illustrated by the following tabulation:

	Expected Service Life of Standard Commercial Equipment - Years		
Component	Severe Exposure	Moderate Exposure	Mild Exposure
Compressor, motor, controls and cabinet	5	10	15
Air cooled, plate-fin condenser	1-2	4-6	10-15

Thus, it can be expected that in severe exposure locations such as Guam and Diego Garcia the standard commercial, uncoated condenser--i.e. a plate-fin unit with aluminum fins[4] mechanically attached to a copper tube--might have to be replaced as often as three times during the lifetime of the unit. This compares to a single replacement in moderate environments such as Pearl Harbor and coastal CONUS locations, or even less frequently in mild environments at semi-desert, interior locations in the Southwest U. S. such as El Centro, CA or Phoenix, AZ.

Expected performance characteristics of selected coil alternates in a severe marine environment are as follows:

Lifetime Coil

a. Performance -- No significant performance degradation or failure over the physical lifetime of other unit components.

b. Cost -- Maximum cost of unit 1.8 times cost of standard commercial unit; replacement coil cost no more than 4.0 times cost of standard commercial coil.

c. Candidate materials -- All copper coil with hot dipped tin or electroless nickel (MIL-C-26074A) coating of 1.0 mil minimum thickness.

d. Design criteria for coil sizing -- Inlet air temperature 100^{o}F; condensing temperature 120^{o}F.

Superior Coil

a. Performance -- Coil performance satisfactory over physical lifetime of other components in comfort cooling unit application, within acceptable

[4] Industry practice is to use 7072 high-strength zinc alloy fin stock of approximately 0.006" thickness with integral, flared "collars" around holes punched for the copper tubes. These collars serve to separate the fins at spacing of 12-14 fins per inch, covering and protecting the soft copper tube after it is expanded into them by either hydraulic

(cont'd next page)

limits of degradation. Possibility of 50% that coil replacement will become necessary in essential refrigeration or equipment cooling installations, where performance degradation cannot be permitted.

b. Cost -- Maximum cost of unit 1.5 times cost of standard commercial unit; replacement coil cost no more than 3.0 times cost of a standard commercial coil.

c. Candidate materials -- All copper coil with surface pre-treatment and organic coating, or standard coil construction using electroless nickel (MIL-C-26074A), pre-coated aluminum fin stock and tin or nickel plated copper tubing, with suitable organic coating. Alternate coating for standard coil is 3.0 mil thickness Heresite baked phenolic resin coating (MIL-C-18467A).

d. Design criteria for coil sizing -- Inlet air temperature 95°F; condensing temperature 120°F.

Improved Coil

a. Performance -- At least one coil replacement necessary over lifetime of unit.

b. Cost -- Maximum cost of unit 15% more than cost of standard commercial unit; replacement coil cost no more than 1.5 times cost of standard commercial coil.

c. Candidate materials -- Standard commercial or all aluminum coil with chromate conversion treatment (MIL-C-5541B) after fabrication, and suitable organic coating.

d. Design criteria for coil sizing -- Inlet air temperature 95°F; condensing temperature 125°F.

In moderate or mild environments longer coil lifetimes and fewer coil replacements would be expected; this factor is taken into consideration quantitatively in developing the life-cycle cost estimates[5] of tables 1 through 4.

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4 (cont'd)
or mechanical means. The copper tubing is usually proof tested at 450 psi. When aluminum tubing is used, it is typically a high ductility 3003 manganese alloy slightly lower in the electromotive series than the 7072 fins. This difference affords some protection from galvanic corrosion. Aluminum tubing is also expanded into the collared, plate-type fins, eliminating the severe corrosion that formerly resulted from residual brazing salts when all aluminum condensers were first introduced.

5 In addition to NAVFAC P-442, a useful discussion is contained in "Analyzing HVAC Life-Cycle Economics on a Calculator", by Robert A. Walker, Specifying Engineer, November 1978

Table 1
Payout and E/C Ratio for Selected Air Condensing Coil Designs[a]
of 10-Ton Air Conditioning and Equipment Cooling/Refrigeration Installations
in Severe Environment - Guam, M.I.

	Estimated Cooling System Installation Cost	Estimated[b] 30-Year Life-Cycle Cost	Annualized Life-Cycle Cost	Estimated[c] Annual Power Consumption (kWhr)	Payout (Years)		Energy/Cost (E/C) Ratio[d] (KBtu/$)	
					Compared to Least Cost	Incremental	Compared to Least Efficient	Incremental
Air Conditioning								
Standard Coil	36,000	144,660	14,625	105,560	Basis	Basis	Basis	Basis
Improved Coil	37,440	134,500	13,600	98,550	1.40	1.40	56.5	56.5
Superior Coil	41,940	133,060	13,450	78,840	5.06	30.0	52.2	50.8
Lifetime Coil	44,640	128,400	12,980	71,610	5.25	5.74	45.6	31.1
Eqpt. Cooling/ Refrigeration								
Standard Coil	36,000	138,180	13,970	95,000	Basis	Basis	Basis	Basis
Improved Coil	37,440	128,460	12,990	88,700	1.47	1.47	50.8	50.8
Superior Coil	41,940	128,230	12,965	70,960	5.91	180	46.9	45.7
Lifetime Coil	44,640	124,030	12,540	64,500	6.04	6.35	40.9	27.75

Notes

[a]Involves combination of material for fins and tubing, protective coating/finish, and coil size.

[b]Net present value, per NAVFAC P-442, includes periodic equipment/component replacement, preventive maintenance, and power. Assumed equipment life 5 years; power cost 3.01¢/kWhr (1978).

[c]Assumes coil washed regularly; power consumption approximately 15% and 25% higher if coil washed infrequently or never, respectively.

[d]E/C Ratio = 11.6 x kWhr/$. Energy Conservation Investment Program (ECIP) requires minimum E/C ratio of 20 for FY-81. Projects must also amortize within their economic life. Ref: CNO ltr Ser. 44/720848 of 27 Jul 78 and ASD (I&H) memo of 21 Oct 77.

Table 2
Payout and E/C Ratio for Selected Air Condensing Coil Designs[a] of 10-Ton Air Conditioning and Equipment Cooling/Refrigeration Installations in Moderate Environment - Pearl Harbor, HI

	Estimated Cooling System Installation Cost	Estimated[b] 30-Year Life-Cycle Cost	Annualized Life-Cycle Cost	Estimated[c] Annual Power Consumption (kWhr)	Payout (Years)		Energy/Cost (E/C) Ratio[d] (KBtu/$)	
					Compared to Least Cost	Incremental	Compared to Least Efficient	Incremental
Air Conditioning								
Standard Coil	26,000	91,910	9,290	70,390	Basis	Basis	Basis	Basis
Improved Coil	27,040	90,850	9,185	65,700	9.91	9.91	55.3	55.3
Superior Coil	30,290	83,540	8,445	52,560	5.07	4.39	48.2	46.9
Lifetime Coil	32,240	83,020	8,395	47,750	6.97	39.0	42.1	28.6
Eqpt. Cooling/ Refrigeration								
Standard Coil	26,000	98,530	9,960	79,170	Basis	Basis	Basis	Basis
Improved Coil	27,040	97,040	9,810	73,910	6.93	6.93	58.7	58.7
Superior Coil	30,290	88,500	8,950	59,130	4.25	3.78	54.2	52.8
Lifetime Coil	32,240	87,515	8,850	53,710	5.62	19.5	47.3	31.2

Notes

[a] Involves combination of material for fins and tubing, protective coating/finish, and coil size.

[b] Net present value, per NAVFAC P-442, includes periodic equipment/component replacement, preventive maintenance, and power. Assumed equipment life 10 years; power cost 3.70¢/kWhr (1978).

[c] Assumes coil washed regularly; power consumption approximately 15% and 25% higher if coil washed infrequently or never, respectively.

[d] E/C Ratio = 11.6 x kWhr/$. Energy Conservation Investment Program (ECIP) requires minimum E/C ratio of 20 for FY-81. Projects must also amortize within their economic life. Ref: CNO ltr Ser. 44/720848 of 27 Jul 78 and ASD (I&H) memo of 21 Oct 77.

Table 3
Payout and E/C Ratio for Selected Air Condensing Coil Designs[a] of 10-Ton Air Conditioning and Equipment Cooling/Refrigeration Installations in Moderate Environment - Charleston, S.C.

	Estimated Cooling System Installation Cost	Estimated[b] 30-Year Life-Cycle Cost	Annualized Life-Cycle Cost	Estimated[c] Annual Power Consumption (kWhr)	Payout (Years) Compared to Least Cost	Payout (Years) Incremental	Energy/Cost (E/C) Ratio[d] (KBtu/$) Compared to Least Efficient	Energy/Cost (E/C) Ratio[d] (KBtu/$) Incremental
Air Conditioning								
Standard Coil	20,000	46,570	4,710	35,190	Basis	Basis	Basis	Basis
Improved Coil	20,800	47,360	4,790	32,850	Nil	Nil	33.9	33.9
Superior Coil	23,300	46,250	4,675	26,280	94.3	21.7	31.3	30.5
Lifetime Coil	24,800	47,490	4,800	23,870	53.3	Nil	27.4	18.6
Eqpt. Cooling/ Refrigeration								
Standard Coil	20,000	62,450	6,315	68,610	Basis	Basis	Basis	Basis
Improved Coil	20,800	62,190	6,285	64,060	26.7	26.7	66.0	66.0
Superior Coil	23,300	58,110	5,875	51,250	7.5	6.1	61.0	59.4
Lifetime Coil	24,800	58,270	5,890	46,550	11.3	Nil	53.3	36.3

Notes

[a] Involves combination of material for fins and tubing, protective coating/finish, and coil size.

[b] Net present value, per NAVFAC P-442, includes periodic equipment/component replacement, preventive maintenance, and power. Assumed equipment life 10 years; power cost 2.33¢/kWhr (1978).

[c] Assumes coil washed regularly; power consumption approximately 15% and 25% higher if coil washed infrequently or never, respectively.

[d] E/C Ratio = 11.6 x kWhr/$. Energy Conservation Investment Program (ECIP) requires minimum E/C ratio of 20 for FY-81. Projects must also amortize within their economic life. Ref: CNO ltr Ser. 44/720848 of 27 Jul 78 and ASD (I&H) memo of 21 Oct 77.

Table 4
Payout and E/C Ratio for Selected Air Condensing Coil Designs[a]
of 10-Ton Air Conditioning and Equipment Cooling/Refrigeration Installations
in Mild Environment - El Centro, CA

	Estimated Cooling System Installation Cost	Estimated[b] 30-Year Life-Cycle Cost	Annualized Life-Cycle Cost	Estimated[c] Annual Power Consumption (kWhr)	Payout (Years)		Energy/Cost (E/C) Ratio[d] (KBtu/$)	
					Compared to Least Cost	Incremental	Compared to Least Efficient	Incremental
Air Conditioning								
Standard Coil	23,400	73,670	7,450	70,390	Basis	Basis	Basis	Basis
Improved Coil	24,340	71,710	7,250	65,700	4.70	4.70	57.9	57.9
Superior Coil	27,260	67,630	6,840	52,560	6.33	7.12	53.6	52.2
Lifetime Coil	29,020	70,920	7,170	47,750	20.1	Nil	46.7	31.7
Eqpt. Cooling/ Refrigeration								
Standard Coil	23,400	78,940	7,980	79,170	Basis	Basis	Basis	Basis
Improved Coil	24,340	76,630	7,750	73,910	4.09	4.09	64.9	64.9
Superior Coil	27,260	71,570	7,235	59,130	5.18	5.67	60.2	58.7
Lifetime Coil	29,020	74,490	7,530	53,710	12.5	Nil	52.6	35.7

Notes

[a] Involves combination of material for fins and tubing, protective coating/finish, and coil size.

[b] Net present value, per NAVFAC P-442, includes periodic equipment/component replacement, preventive maintenance, and power. Assumed equipment life 15 years; power cost 2.94¢/kWhr (1978).

[c] Assumes coil washed regularly; power consumption approximately 15% and 25% higher if coil washed infrequently or never, respectively.

[d] E/C Ratio = 11.6 x kWhr/$. Energy Conservation Investment Program (ECIP) requires minimum E/C ratio of 20 for FY-81. Projects must also amortize within their economic life. Ref: CNO ltr Ser. 44/720848 of 27 Jul 78 and ASD (I&H) memo of 21 Oct 77.

Life-Cycle Costs

In the pay-outs and energy/cost ratios tabulated for each of the selected locations in tables 1 through 4, the first four columns deal with life-cycle costs. A 10-ton unit was selected as the basis for cost comparison because the size range of five to twenty tons at PMTC/NAS Pt. Mugu, considered reasonably representative, contained almost half of the 250 cooling unit installations at that location. The basic installation cost, including both the refrigeration and distribution subsystems, was assumed to be equal for typical air conditioning and equipment cooling/refrigeration installations. At different locations, installation costs (column 1) were adjusted for the geographic construction cost factor of NAVFAC P-448. The net present value (column 2) combines investment and all operating and maintenance costs, including periodic replacement of condensers as well as replacement of complete cooling units. This was summed over a 30-year period of comparison for installations having units with 5, 10, and 15-year lifetimes, and was calculated using discount factors of NAVFAC P-442. A differential inflation rate of 7% for the cost of electrical energy was also applied per current ECIP guidance. In comparing columns 1 and 2, it is of interest to note that a MILCON investment of $1.00 in cooling facilities also commits the Navy to the simultanrous allocation of between $1.91 and $4.02 for 30-year operation and maintenance, depending on location. Column 3 is simply the equivalent annual cost of the totals from column 2. Column 4 is included to permit calculation of E/C ratios and as an easy comparison of power consumption[6], since power costs are not separated from the totals of colums 2 and 3. For standard coils, power cost typically ranges between 1/3 and 2/3 of the total annualized life-cycle costs; maintenance ranges between 6% and 10%, with capital costs for the initial installation and major equipment replacement varying between 28% and 54% of the total.

A significant power cost factor is frequency of coil washing. Periodic coil washings should be part of a station's preventive maintenance program. Calculations of life-cycle costs included a preliminary evaluation of more rapid coil performance degradation and added power consumption when coils were not washed regularly. Infrequently washed or unwashed coils subject to airside fouling in marine atmospheres were estimated to result in higher power costs of approximately 15% and 25%, respectively.

Pay-Outs and Energy/Cost Ratios

The last four colums of tables 1-4 present simple pay-outs and energy/cost ratios, using data from the first four columns. For both pay-out and E/C ratio, comparisons are made to the least cost or least efficient standard coil and to the next least expensive coil alternative. Thus, the

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6 Power consumption estimates are based on running time, a rational analysis of which is contained in Code L03B file memo dated 9 April 1979 entitled, "Estimating Energy Requirements Based on Relative Heat Transfer"

improved coil is compared only to the standard coil but the superior coil is compared to both the standard coil and the improved coil while the lifetime coil is compared to the standard coil and to the superior coil. The incremental pay-out or E/C ratio of the next level of expenditure for higher performance coil is shown in colums 6 and 8. With a sufficiently good pay-out for the improved over the standard coil, there may be a relatively poor (or non-existent) pay-out for the superior over the improved coil, and the superior coil will still show a relatively good pay-out over the standard coil. A case in point is the superior coil for Guam, table 1. In this instance, higher performance than provided by the improved coil, cannot be justified under the assumptions made for the tabulated example. (Note the 30 and 180-year pay-outs in column 6.) However, at Pearl Harbor the reverse situation exists. At that location superior coils for both air conditioning and equipment cooling/refrigeration show good incremental pay-outs and improved pay-outs relative to the standard coil when compared to the improved coil. At Charleston (table 3) there appears to be no Navy cost advantage attending the use of any higher performance coils, while at El Centro the superior coil should probably be given serious consideration, as at Pearl Harbor.

On the basis of energy saving, all coils will satisfy the requirement of CNO guidance that a $1,000 investment result in a saving of at least 20 million BTUs set for the FY81 MILCON Program. (A single exception is the incremental cost of the lifetime air conditioning coil over the superior coil at Charleston, table 3, where the E/C ratio falls to 18.6.)

Variations at the four comparison sites from coil to coil and between dollar pay-out and E/C ratios are more understandable when it is remembered that the pay-out calculations over a thirty year time span involve large costs for both power and condenser equipment replacement while the E/C calculations involve power consumption only.

The Status of Research & Development for Improving the Long-Term Performance of Air-Cooled Condensers in Marine Environments

I. DIMENSIONS OF THE CORROSION/FOULING PROBLEM

The Department of Defense Construction Criteria Manual (reference 1, chapter 8, pp. 8-15) makes mandatory the outdoor installation of air-cooled condensers, evaporative condensers and cooling towers. But it also acknowledges that some problems may result by its statement:

> "In order to avoid corrosion problems, no air conditioning equipment, including rooftop units, shall be installed on the roof of a building within two miles of the ocean. When such equipment is installed on the ground, it should be located on the leeward side of the building. Special consideration of corrosion problems shall be made for any air conditioning (including heating and ventilating) equipment which is to be installed within ten miles of the ocean."

Nevertheless, the majority of Navy air conditioning and refrigeration/equipment cooling installations employing air-cooled condensers appear, of necessity, to have been installed closer to the ocean than the two and ten-mile DoD limits would normally permit. Although operating and maintenance costs may be higher than at interior locations, little design consideration is given to such special conditions. The reason is mechanical cooling equipment has become standardized to such an extent that custom designs are discouraged. Clearly, standardization has reduced the cost of an initial installation. What is not so clear is whether this gain has been accomplished in exchange for an even greater loss due to the resulting increase in operating expense and replacements.

The Design Problem of Fouling

A design engineer will normally match the capacity of a compressor and a condenser to load requirements, following reference 1, which states:

> "In the selection of air-cooled condensers, careful engineering consideration shall be given in the determination of the capacity of the condenser and the condenser fan (or fans) in relation to the compressor size. Often the selection of a larger capacity condenser will permit use of a smaller compressor motor so that total electrical input to both condenser and compressor is reduced. In other cases where the compressor motor size cannot be reduced, the electrical consumption of a given size compressor can be reduced by using a larger capacity condenser and, therefore, the combined electrical input to both components can be reduced. Capacities of air-cooled condensers shall be selected to provide optimum operating costs over the life of the equipment, consistent with initial equipment costs. Full consideration shall be given to the use of air-cooled condensers for all reciprocating refrigeration compressors unless there are compelling technical or economic reasons for using water cooling."

Additionally, he will be guided by reference 2 which also addresses the economical selection of air-cooled condensers. This NAVFAC manual establishes limits on maximum design condensing temperature and minimum temperature difference between the condensing refrigerant and entering air. No reference is made to power cost or other factors affecting life-cycle performance, from which the inference may be drawn that condenser selection economics deals primarily with initial cost. An experienced designer realizes, however, that in selecting his entering air and condensing temperatures he is indirectly prescribing a fouling factor for the condenser he is sizing. This is necessary because references 2 and 3 give no guidance in this area, as they do for water cooled condensers, nor do they address the subject or provide information to make allowance for corrosion effects on condenser life and efficiency. Thus, the design trade-off among factors which affect life-cycle system cost is largely left to the experience of an equipment manufacturer/supplier. It is well-known that the technical output of an equipment supplier is very difficult, if not impossible, to control under current procurement regulations. The complexity of the resulting design problem of economic condenser selection can be illustrated most simply by a listing of the design-economic variables involved, as is done in the following tabulation.

Site Variables	Design Variables	Oper. Variables
Corrosion/fouling conditions	Condenser size	Load factor
Labor cost/skills/availability	Materials for tubes/fins	Operating factor
Construction/maintenance cost index	Coated/uncoated	Level of preventive maintenance
Power costs	Coating material	Washed/not washed
		Washing frequency

The Corrosion Problem

Industry recognizes that the performance of its standard designs can become deficient because of atmospheric corrosion in marine environments. Less efficient condenser heat transfer due to corrosion increases the condensing temperature and pressure with a reduction in cooling capacity, an increase in motor load/power consumption, and more rapid compressor deterioration. It is not unusual for aluminum condenser fins to corrode away completely in two years or less. Several air conditioning manufacturers report a two year maximum coil lifetime expectancy in certain Texas Gulfcoast and Southern California coastal locations. The Army Mobility Equipment Research and Development Center considers that a one and one-half year condenser lifetime is acceptable performance at Ft. Sherman in the Panama Canal Zone. A 1969 CEL report to NAVFAC on materials for air conditioners states:

"The lifetime of an air conditioner condenser with aluminum fins on copper tubes at Kwajalein is about one year. Corrosion is

visible in less than two months in units installed near the ocean. Larger units of central air conditioning systems using copper fins on copper tubes last three to four years depending on exposure. On Guam, the situation is about the same, given similar exposures. Units run 24 hours per day in both places."

Of fourteen 3/4-ton air conditioners installed on Guam for a Civil Engineering Laboratory field test in June 1970, six had experienced mechanical failure and were replaced by October 1971. Prior to this experience, the Laboratory had stated:

"Corrosion of heat exchangers--especially the aluminum fin/copper tube condensers usually supplied in air conditioners--is a continuing expense for replacement or repair. In the warm humid salt air of the tropic islands the problem is especially severe. Aluminum fin/copper tube condensers are destroyed by galvanic corrosion while fins of all copper condensers are destroyed by oxidation. Three to five years is now the expected service life on Guam."

In less severe environments, it has been observed that rooftop units at the NCBC, Port Hueneme Commissary show extensive coil deterioration and will require replacement after less than ten years' service. Similar conditions exist at Pt. Mugu. On the other hand, condensing units with tin-dipped, all-copper coils, serving portable, walk-in refer boxes at Pt. Hueneme are still giving satisfactory service after 25 years.

Problem Magnitude

The magnitude of corrosion/fouling problems at Navy shore facilities can be measured by the size of the Navy inventory of air-cooled mechanical refrigeration installations. Such a size estimate was made as part of this investigation in order to assess the potential benefit of a solution.

Using preliminary results reported in NESO's Air Conditioning Tune-Up (ACTUP) Program equipment survey, combined with data from Pt. Mugu on installed units of all sizes and types, it was estimated that there is somewhat under 300,000 tons of installed capacity in air-cooled refrigeration and air conditioning equipment, Navywide, in sizes as large as 480 tons for a single unit. The estimated breakdown of large and small air-cooled units is as follows:

	Tonnage		Units	
	Amount	Percent	Number	Percent
Units of 50-ton capacity & over	58,000	21.4	590	4.0
Units under 50-ton capacity	213,000	78.6	14,300	96.0
	271,000	100.0	14,890	100.0

Considering both air-cooled and water-cooled equipment, the Navy is estimated to be operating a total of 15,500 units that produce 397,000 tons of refrigeration. Of this amount, an estimated 600 large water-cooled units represent 31.6% of the Navy's total intalled air conditioning and refrigeration/equipment cooling capacity.

For cost estimating purposes, it is desirable to break down the total tonnage of equipment employing air-cooled condensers in two ways. First, by severity of atmospheric conditions to which condensers are exposed, and second, by the type of service, i.e., whether the units are used continuously or run only during the hot portion of the day or the year, such as for comfort cooling. The former breakdown permits a more accurate estimate of equipment replacement frequency, the latter is necessary for meaningful estimates of power consumption and costs. The preliminary ACTUP inventory results gave geographical equipment statistics by Engineering Field Division which were extrapolated to yield the following sub-divisions of the total tonnage estimate for air-cooled units:

	Conditions of Exposure			
	Severe	Moderate	Mild	Total
Installed tonnage of air conditioning equipment	14,500	62,700	4,800	82,000
Installed tonnage of refrigeration & cooling equipment	25,300	143,500	20,200	189,000
	39,800	206,200	25,000	271,000

II. MILITARY RESEARCH AND DEVELOPMENT

The problem outlined above is not new. It has existed and has been recognized for over 20 years, changing slowly with developments in materials and manufacturing technology, with increases in the cost of labor for field installation and maintenance, and, most recently, with the expected accelerating costs for electric power. The results of prior materials sciences research and equipment performance studies by military laboratories take on an added significance now because their implementation may effectively reduce electrical energy consumption.

Navy Research and Development

Recognizing that condenser choices for selection in accordance with prescribed criteria were frequently limited and that commercially available equipment often failed to perform satisfactorily in severe marine environments, NAVFAC authorized two four-year research investigations by the Civil Engineering Laboratory (CEL), which began in 1968. Both investigations are now completed. The first dealt with materials to improve the corrosion resistance of air-cooled condensers and the second with a two-year weathering test of three selected organic coatings which could increase the long-term heat transfer coefficient of such condensers.

Over the period FY69 through FY72 CEL conducted the field test of fourteen air conditioning units at Guam referred to previously. Twelve modified and two unmodified units were tested to evaluate the corrosion control value of various metals and coatings for condensers, valves and fittings in air conditioners. Mechanical failures terminated the test before corrosion effects became evident. Between FY75 and FY78 CEL undertook to determine, by laboratory experiment, the long-term effect of protective coating on the thermal performance and material deterioration of fin-tube air-cooled heat exchangers. The total cost of CEL work since 1969 was slightly over $100,000.

The completed coating research was successful within its authorized scope. It indicated a possible long-term beneficial effect of protective coatings on the thermal performance of fin-tube type air-cooled heat exchangers of various materials of construction. Thus, it provides the technical basis for a decision whether or not more extensive research on coatings for air-cooled refrigeration condensers should be conducted. Contrary to the expectations of a number of practicing engineers, findings indicated that substantial benefit, i.e., over 50% improvement compared to an uncoated coil, might be realized for a representative coating under laboratory simulated conditions. Specifically, the following conclusions can be drawn from the draft report of reference 4:

a. Reported results show that favorable effects on heat transfer can be expected for organic coatings, based on two years' exposure under laboratory conditions.

b. Test results do not permit the condenser materials/coatings to be classified as "high performance" or "improved" refrigeration condensers, nor to make recommendations to NAVFAC on design criteria or specifications for refrigeration equipment.

c. Performance of the three organic (paint) coatings tested do not provide a basis for selecting among the many other types of available commercial and MIL-SPEC coatings tested by CEL and/or developed for automotive, ordnance, and aerospace equipment.

d. Test results do not provide a basis directly for predicting the condenser life expectancy or the cooling unit power consumption under various conditions of operation and exposure.

Factors other than condenser material selection and coating, such as the method of condenser fabrication, condenser size, and the frequency of condenser washing, have an equal or greater effect on condenser life and cooling unit power consumption. Therefore, items (b), (c), and (d) are appropriate subjects for continuing research.

Army Research and Development

Civil Engineering Laboratory work to improve the performance of air-cooled refrigeration condensers in marine environments was based, in part, on previous work by the Army Mobility Equipment Research and Development

Center (formerly the U. S. Army Engineer Research and Development Laboratories) at Ft. Belvoir, VA. This laboratory pursued a test and evaluation program between FY55 and FY73, concentrating on lightweight, all aluminum plate-fin type (as contrasted to fin-tube type) coils for mobile equipment. Initial laboratory salt-fog tests per ASTM B-117-49T were made on condenser coils with various combinations of conventional materials and on all aluminum coils, both coated and uncoated. Successful laboratory performance of aluminum coils was followed by a field test at Ft. Sherman, Panama Canal Zone, of twelve 3/4-ton air conditioning units in which condensing coils were fabricated of different aluminum alloys, some being coated with paint and/or selected chemical conversion coatings. References 5 and 6 report on this work. Performance of the all-aluminum coils in the Panama air condenser field test led to an investigation of the effects of brazing for fin attachment which is reported in references 7 and 8. Pressurized coils subjected to fan-circulated marine air were exposed at Ft. Sherman to evaluate coatings for brazed coils and for coils with mechanically bonded fins, which were just being introduced to remedy corrosion from residual brazing salts. These tests determined the leakage failure from pitting of six plate-fin type and two fin-tube type, all aluminum coils. Heat transfer was not measured. The final report abstract states:

> "The results of the test program indicates that all-aluminum condensers may be substituted for the copper tube/aluminum fin construction currently used in military environmental control units in the interest of cost savings. However, care should be exercised at the tube joint with any dissimilar metals, which should be protected with a moistureproof, external seal."

The Ft. Belvoir Laboratory advises that no changes to equipment resulted from these experiments, nor was a "tropicalization" specification prepared.

It is believed that the Army test results spurred industry to develop mechanical bonding techniques for all-aluminum, plate-fin condensers and ultrasonic brazing which eliminates conventional aluminum brazing fluxes for tubing joints. These are now accepted industry practices. Another interesting result was the conclusion that laboratory salt-fog testing was of little value as an accelerated test due to the alternate wetting and drying conditions existing in the field. Residual brazing salts and atmospheric salt crystals were able to lodge at a fixed point where continuous reaction with the aluminum could occur. In laboratory salt-fog testing a continuous washing action occurred over the surfaces which tends to dilute or weaken concentrated reactive points so that penetration is less rapid than in high-salt natural environments.

III. INDUSTRY DEVELOPMENTS

There are 89 manufacturers listed in the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) 1976 Product Directory as sources of air-cooled condensing units for split systems in the range between three and fifteen tons. Thirty-eight of these manufacturers and an additional six firms make similar equipment in sizes over fifteen tons capacity. With few exceptions, manufacturers in the above groups also make self-contained units of various types in the same size ranges.

As part of this cost/effectiveness investigation, an inquiry questionnaire was sent to eleven equipment manufacturers selected primarily from those who had previously indicated a desire to work with NAVFAC on air conditioning components for a proposed modular building program. Since a number of these manufacturers did not fabricate their own condensers for air-cooled equipment, inquiries on condenser fabrication and coating practice were sent also to three coil fabricators, two coil coaters, and two suppliers of potentially applicable metal finishing products. A number of other industry sources and suppliers, including Reynolds Metals Co., were interviewed by phone. Responses to these inquiries are the source of information for industry practices and current industry developments presented below.

Coil Design and Fabrication

In spite of the myriad of possible combinations in which air conditioning components can be and are assembled to form working systems, the opportunity for custom selection of condensing equipment to be applied in such systems is limited. Compressors, condensers, and condenser fans, are sold as packaged condensing units to be used with remote, direct expansion components. Assembled with direct expansion water coolers and water circulating pumps, compressors and air-cooled condensers are sold also as packaged water chillers for systems when water is circulated as a heat transfer medium. Rooftop units and window air conditioners are typical of another class of equipment package containing direct expansion coils and integral blowers to be used where air is circulated as a heat transfer medium. These units often contain gas furnaces or electric heating elements, or, alternatively can be arranged for year-round operation as heat pumps. Thus, increasingly, cooling equipment manufacturers are selling "packages" in which there is no design option to specify condenser materials or performance.

It is the opinion of the Carrier Corporation Corporate Research and Development Department that industry efforts over the years have resulted in a highly cost-effective air condenser for package units; and that there would be no advantage whatsoever for any kind of coating, or returning to all-copper condensers for good, long-term performance at normal, inland locations. However, a number of other manufacturers indicated that they are actively pursuing, or interested in becoming involved in, or are following closely potential coating applications. Presumably, coatings are seen as having competitive advantage because the same manufacturers, in general, indicated that they were responding in various

ways to customer demand for improved efficiency. Reference 9 is intended to be the basis for efficiency labeling of industry's consumer products. Catalogs on industrial package units now provide information on a unit's energy efficiency ratio (EER) which is defined as BTUs per watt-hour. However, catalogs give only the design value; no information was provided by any questionnaire respondent on the value of this performance parameter over time or under typical field conditions.

Even though condenser design seems fairly well standardized throughout the industry, proprietary details are probably involved because no respondent provided data on the heat transfer factor used for sizing coils in his package designs*. For industrial, air-cooled condensers a plate-fin coil is normally used. It has copper tubing for easy piping assembly by brazing, and aluminum fins for economically providing a large convective heat transfer surface. Fins are of 7072 high-strength zinc alloy aluminum with collars, which are flared openings through which the copper refrigerant tubing is inserted. The collars provide sufficient spring so that a good mechanical bond and effective heat transfer results when the copper tubing is mechanically expanded into them. The collars space the fins, typically 12-14 fins per inch. They also cover the copper tube with aluminum, which may limit the severity of galvanic corrosion. Several tubes pass through each fin and are joined at the end by return bends. Fins are usually flat, but may also be configured to create turbulence for improved heat transfer. Because fin thickness is typically only 0.006", the assembly is subject to damage in handling and the fins themselves can deteriorate physically from corrosion in adverse environments. The aluminum fin material is anodic to the copper tubing, i.e. is consumed when a galvanic couple is established by any aqueous surface film of electrolyte such as ocean spray. The galvanic potential difference between copper and aluminum is 0.45 volts, a difference which is almost double the 0.25 volt maximum suggested for reducing intermetallic contact problems by reference 10.

The aluminum industry has been promoting the adoption of an all-aluminum condenser for many years. Success has been achieved only recently, since the introduction of an ALCOA developed process of ultrasonic brazing. This process eliminates the corrosion caused by a residue of salts that are difficult to remove after brazing with conventional fluxes. A large percentage of mass-produced window air conditioning units now have all-aluminum coils, fabricated in much the same way as the more conventional copper tube/aluminum fin coil described above. Trane Co. air-cooled rooftop a[redacted]-15 ton size range have all aluminum coils; units of 20 ton capacity and above have the conventional copper/aluminum coil. Automotive oil and transmission coolers and some automotive radiators are now also being made of aluminum. These units have been successfully protected from the corrosive effects of salts applied to roads for ice melting with a chromate conversion coating followed by paint.

* This should not be taken as an indictment because condenser performance is normally obtained from tables of face area, depth, air velocity, and temperature difference.

Custom coils are available from both large and small air conditioning manufacturers on industrial units that are custom assembled. The old industry standard, tin-dipped copper coil can be obtained at a premium of 30% to 60%, depending upon the unit; the coil itself costs about three times as much as the standard copper tube/aluminum fin coil. Because of coil design difference, the increased all-copper coil lifetime is achieved at some possible sacrifice of initial coil capacity and efficiency. Other metals such as stainless steel are also available. The least expensive possibility for improved fin corrosion resistance is the use of standard aluminum fin stock pre-coated before fabrication of the fins. The York Division of Borg-Warner Corporation is investigating Kanigen electroless nickel pre-coating which conforms to MIL-SPEC 26074A.

Coil Coating

If an industry standard for condenser coil coating can be said to exist, based on usage for only a fraction of 1% of the total tonnage, it is Heresite coating. Heresite provided good protection in the Army's Panama, Canal Zone test. This coating is applied by a proprietary method developed specifically for finned coils using a baked, phenolic resin base material which conforms to MIL-C-18467A. The multiple coat finish has a dry film thickness of 3 mils with sufficiently good thermal conductivity that no increased coil surface allowance is recommended for coated coils. The Trane Co. amd many smaller manufacturers use Heresite for condenser and evaporator coils in corrosive atmospheres. Coils must be shipped to Manitowoc, Wisconsin, for coating, which typically adds about 50% to the cost of a five-ton unit and 30% to the cost of a fifteen-ton unit.

Relative to energy savings in severe marine environments, it is the opinion of Trane Co. engineers that coil coatings would be less cost effective than periodic condenser washing with fresh water. Their operating manuals recommend condenser washing at the beginning of the cooling season and once a month thereafter. They concur with the conclusion of this analysis that a 15% to 25% increase in power consumption over the equipment lifetime is reasonable if regular condenser washing is not part of a station's preventive maintenance program.

Many manufacturers of packaged mechanical cooling equipment purchase their condensers from other firms who specialize in coil fabrication. What limited industry research and development has been done on coil coatings has been done by coil fabricators. The Bohn Heat Transfer Divison of Gulf & Western Manufacturing Company, has developed a line of coatings known as Bohn-Kote. Bohn-Kote No. 1 has been used successfully for dip coating wet condensers in marine environments. However, it is suitable only for small coils. It is expensive because the material has a 24-hour maximum pot life. Bohn-Kote Nos. 2 and 3 have been used by other coil fabricators as a substitute for Heresite.

Bohn is currently investigating a new Dow-Corning material that is reported to give protection equivalent to anodizing for aluminum coils. They feel that they already have a good method of surface preparation in Alodine 1200, a chromate conversion coating qualified under MIL-SPECS C-5541B and C-81706. They are prepared to do production coating in-house when they find a suitable material.

The Wilmington Coil Division of Singer Co. coats all small coils, in-plant by dipping; they have experimented unsuccessfully with plastic and pehnolic coatings that could be quoted as less expensive substitutes for Heresite.

McQuay-Perfex has developed a vinyl chloride coating which has been tested successfully in a coastal Florida location for performance comparison with Heresite. Because of its toxicity, this coating is not used for batch dipping of assembled coils. It is claimed to have potential for pre-coating fin stock.

IV. AVAILABLE COATING TECHNOLOGY

In dealing with air conditioning equipment and its protection from corrosion, consideration must be given to the extensive array of metal finishing technology that has arisen in the manufacture of automotive, ordnance, and aerospace equipment used by the military, including the Navy and Marine Corps. A great deal of this technology, although to some extent proprietary, is covered by military specifications. It may be more applicable to coatings for heat exchangers than coatings used in construction and maintenance of facilities, which is the area where CEL has done the majority of its coating research. Thus, this investigation included a review of industrial metal finishing practices summarized by reference 10 and the industry guidebook of reference 11. For organic finishes, reliable data on severe atmosphere performance of a number of paint coatings is contained in references 12 through 14. Unfortunately, comparable data is not available on inorganic metallic coatings and chemical surface treatments for non-ferrous condenser coil materials. What data does exist from industry experience is fragmentary and highly subjective; documented results of exposure tests on which to base engineering judgment would certainly be desirable. Cost data is more readily available; costs for selected finishes are summarized by the attached tabulation.

Coatings of Interest

Coatings of particular interest for further laboratory or field testing include:

Electroless Nickel, MIL-C-26074A -- This coating is ductile, dense and impervious with good abrasion resistance. It can be applied to both copper and aluminum, before or after fabrication. Being chemically deposited, uniform coatings are possible on irregular surfaces. Coatings as thin as 3/10 mil provide satisfactory protection.

Heresite, MIL-C-18467A -- Material applied by a proprietary process developed particularly for fin coils. Industry preferred coating.

Chromate Conversion Coating, MIL-C-5541-B (Material), MIL-C-81706 (Application) -- Chemically produced, chromate conversion coatings can be applied uniformly on irregular surfaces such as completely assembled condenser coils. This coating has good thermal conductivity and, in itself, provides a high level of corrosion protection for aluminum. It is inexpensive and is also an excellent base for further paint coating. Possibly, it is not of sufficient abrasion resistance to be used for pre-coating fin stock.

Electrostatic Polyester Dip Coating -- Uniform dip coatings are difficult to obtain on fin coils with some conventional paints. The evaporation of solvents from the coil interior can reduce the coating thickness on exterior portions of the fins. Electrostatically deposited coatings such as Sherwin-Williams "Power Clad" enamel will produce a uniform low thermal resistance coating of less than 1 mil thickness.

Other Coatings

Anodized coatings for aluminum provide good corrosion resistance and uniform thickness on irregular surfaces. However, the coating is porous, brittle, and has high thermal resistance. In addition, it is relatively expensive and therefore appears to be less promising than other alternatives. Coatings currently under development for application to solar collectors may have promise eventually, but this technology is not sufficiently advanced at the present time to warrant testing in an air-cooled condenser program.

Coating Selection Considerations

Coil coatings are subject continuously to a higher service temperature than most painted metal surfaces except boiler smokestacks. For coatings like Heresite, which are baked at temperatures up to 450°F, a 150°F maximum coil operating temperature is no decomposition problem. Nor should such temperature be a factor in the service life of a baked coating. Chromate conversion coatings for aluminum are considered limited to 150°F because heating causes dehydration and insolubility of hexavalent chromium compounds. However, they are being used satisfactorily on automotive transmission and engine oil coolers at temperatures up to 300°F.

In a letter to CEL dated 28 Jan 1969 commenting on this Laboratory's planning for its condenser materials research, the Officer in Charge of Construction (OICC) at Mid-Pac cites two experiences with an Air Force equipment specification. Both were involved in litigation. He stated:

"The lesson we have learned is that any improvement to standard commerical units, such as copper fins/copper condenser coils, epoxy coatings, etc., must be coordinated with industry in advance so that procurement sources are readily available upon award."

A discussion of protective coatings in reference 3 (chapter 36 of the 1976 Systems Volume) substantiates this advice and also strongly recommends shop-applied coatings and shop assembly of coated items over field applied coatings or field retrofit.

Typical Costs for Industrial Finishes
Applicable to Coating of Aluminum-Fin Condensers

Type of Industrial Finish	Equipment Mil-Spec.	Range of Cost (1) Dollars per Sq. Ft.
Chemical Finishes		
Conversion Coatings	MIL-C-5541B MIL-C-81706	.01 - .03
Zincate	——	.04 - .08
Electroless Nickel	MIL-C-26074A	See Note 2
Electrolytic Oxide Finishes		
Clear Anodizing	MIL-A-8625, Types I and II	.08 - .30
Hard Anodizing	MIL-A=8625, Type III	.25 - .90
Electroplated Finishes		
(3) Cadmium	QQ-P-416	.10 - .15
(3) Zinc	QQ-Z-325	.15 - .20
Copper	MIL-C-14550	.15 - .60
Copper-Nickel-Chromium	QQ-C-320	.40 - .60
Organic Finishes		
Chemical Treatment & Paint	Various, including TT-C-490, Type III; MIL-C-23377; MIL-P-15328C;TT-P-645; TT-P-489	See note 4 .03 - .10
Baked Phenolic Resin (Heresite)	MIL-C-18467A	See note 5

NOTES:

(1) Except as noted, costs are based on those existing in the industry in 1964, and relate to continuous operations on relatively large flat panels of fin stock prior to fabrication. Add $0.01 - 0.03 per sq. ft. for cleaning.

(2) Roughly equivalent to anodizing. chemical cost $0.50 - 0.75 per sq. ft. per mil thickness; however, only 2/10 - 3/10 mil coating thickness needed. Chemplate Corp. proposes test on actual fin stock as basis for quotation.

(3) Primarily applicable to copper tubing prior to assembling fins. Brush plating after final assembly is possible for areas left unplated for soldering.

(4) Electrodeposited enamel on assembled test coil quoted at $0.01 per perimeter inch, amounting to $25.75, or approximately 50% of coil cost, per coil.

(5) Quotation basis; minimum set-up charge $70.00 per coil.

Sources: Reynolds Handbook, "Finishes for Aluminum, Vol. I", 1967, and MIL-STD 171C, 7 Nov 1972

V. REFERENCES

The numbered references listed below are referred to in the foregoing discussion. In addition, this investigation employed other references in its review of design, estimating, and economic data. These references are listed by subject following the numbered references.

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2. Design Manual, Mechanical Engineering, NAVFAC DM-3, Sep 1972

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   1975--Equipment Volume
   1974--Applications Volume
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24. Military Construction Cost Engineering Data, NAVFAC P-448, Feb 1976

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ARMY MATERIALS & MECHANICS RESEARCH CENTER Dr. Lenoe, Watertown MA
ARMY MISSILE R&D CMD Redstone Arsenal AL Sci. Info. Cen (Documents)
ASO PWD (ENS J.A. Jenkins), Philadelphia, PA
ASST SECRETARY OF THE NAVY Spec. Assist Energy (Leonard), Washington, DC
BUREAU OF COMMERCIAL FISHERIES Woods Hole MA (Biological Lab. Lib.)
BUREAU OF RECLAMATION Code 1512 (C. Selander) Denver CO
CINCLANT Civil Engr. Supp. Plans. Ofr Norfolk, VA
CINCPAC Fac Engrng Div (J44) Makalapa, HI
CNAVRES Code 13 (Dir. Facilities) New Orleans, LA
CNM Code MAT-08T3, Washington, DC; NMAT 08T246 (Dieterle) Wash. DC
CNO Code NOP-964, Washington DC; Code OP 987 Washington DC; Code OP-413 Wash. DC; Code OPNAV 09B24 (H); OP987J (J. Boosman), Pentagon
COMFLEACT, OKINAWA PWO, Kadena, Okinawa
COMCBPAC Operations Off, Makalapa HI
COMNAVMARIANAS Code N4, Guam
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NAVWPNSTA PWO, Seal Beach CA
NAVWPNSUPPCEN Code 09 Crane IN
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NCR 20, Commander
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